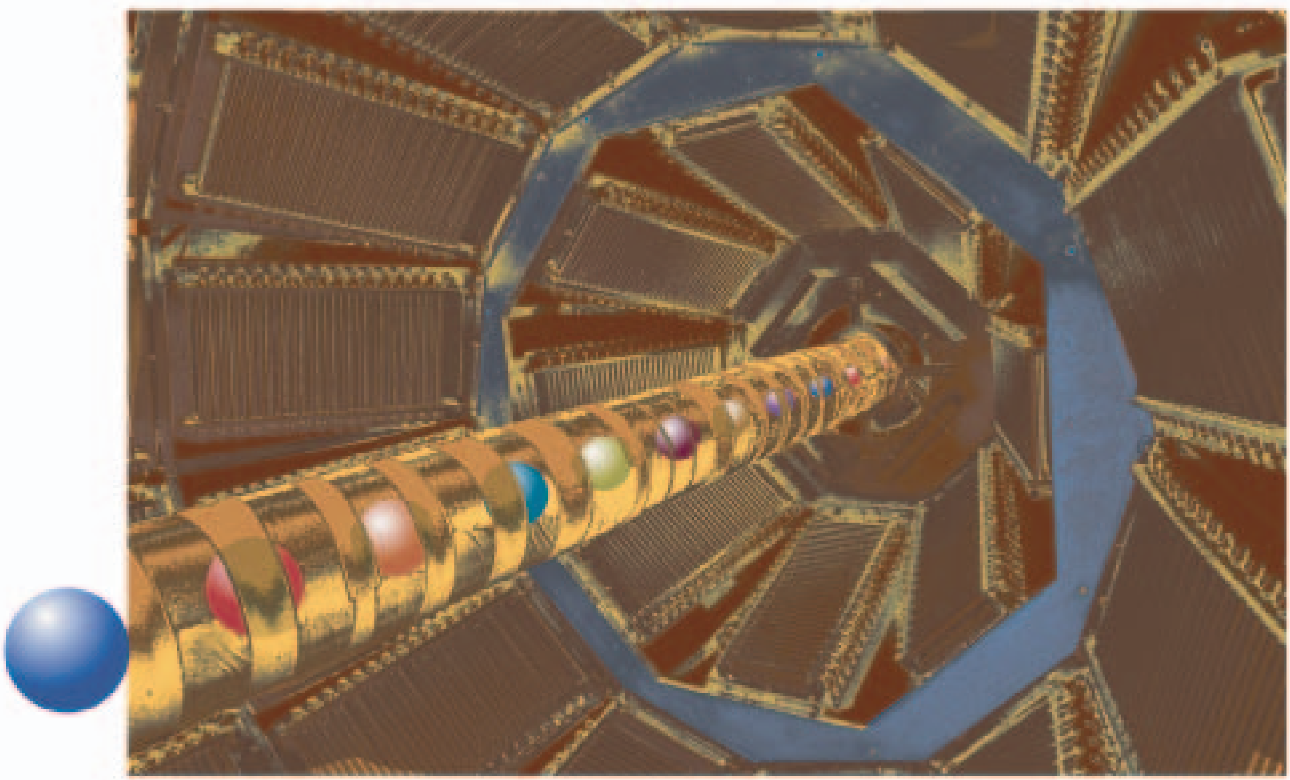
LA-UR-05-8995

Approved for public release;
distribution is unlimited.

*Version 2*

# LANSCE Futures: A Twenty-Year Vision



LA-UR-05-8995

LANSCE Futures: A Twenty Year Vision *Version 2*

November 2005

Los Alamos
NATIONAL LABORATORY
EST. 1943

LA-UR-05-8995
*Version 2*

# LANSCE Futures

## A Twenty-Year Vision


*Technical Editor*
Kurt Schoenberg, *LANSCE-DO*

*Authors*
Brad Bergman, *LANSCE-ABS*
J.D. Bowman, *P-23*
Mike Cappiello, *AFC-PO*
John Eddleman, *LANSCE-MDE*
Jeff Goettee, *ISR-5*
John Hopson, *X-4*
Steve Howe, *X-2*
Alan J.Hurd, *LANSCE-LC*
Mike James, *D-5*
Paul Langan, *B-2*
Stuart Maloy, *MST-8*
Ferenc Mezei, *LANSCE-LC*
G.B. Mills, *P-25*
G.S. Mitchell, *P-23*
Eric Pitcher, *LANSCE-DO*
Rene Reifarth, *LANSCE-NS*
Dan Rusthoi, *AFC-PO*
Larry Rybarcyk, *LANSCE-ABS*
A. Saunders, *P-25*
Dale W. Schaefer, *LANSCE-LC and University of Cincinnati*
Erich Schneider, *D-5*
Kurt Schoenberg, *LANSCE-DO*
Benno Schoenborn, *B-2*
Ron Selvage, *LANSCE-TMS*
Sunil Sinha, *University of California San Diego*
Jacob Urquidi, *New Mexico State University*
Steve Wender, *LANSCE-NS*
W.S. Wilburn, *P-25*
Keith Woloshun, *LANSCE-NS*
Rick Wood, *LANSCE-ABS*



Los Alamos
NATIONAL LABORATORY
EST. 1943

# Contents

7 Executive Summary

13 Introduction

25 Chapter 1
Proton Radiography *and* Physics Certification *of* Nuclear Weapons Primaries

33 Chapter 2
Neutron Scattering: Enabling Materials Science *and* Bioscience Research *at* Los Alamos National Laboratory

49 Chapter 3
Materials Testing: *An* Irradiation Capability *for the* Development *of* Fast Spectrum Systems

59 Chapter 4
Nuclear Science *and the* Physics Certification *of* Nuclear Weapons

73 Chapter 5
Fundamental Nuclear Physics Research

85 Appendix

# Executive Summary

# Executive Summary

The Los Alamos Neutron Science Center (LANSCE) has served the nation for over thirty years as a premier research facility for national security and fundamental science. LANSCE is a cornerstone research facility for scientific enterprise at the Los Alamos National Laboratory—"a destination for scientific excellence" attracting the very best scientific talent. Science and technology are evolving rapidly along with the requirements of the Department of Energy's (DOE) national security, energy, and basic research programs. To meet those future needs, LANSCE requires both refurbishment and enhancement—refurbishment to assure reliable operation and enhancement to meet future scientific and mission requirements.

A twenty-year strategy is proposed to refurbish and enhance the LANSCE accelerator and improve the associated research facilities required for national security, energy security, and fundamental science. This report summarizes this strategy and the mission drivers that set the requirements

## NATIONAL SECURITY AND DEFENSE

*The future of LANSCE is critical to nuclear weapons stewardship*. All three National Nuclear Security Administration (NNSA) laboratories, as well as the UK Atomic Weapons Establishment (AWE), utilize LANSCE's unique facilities to address scientific issues necessary for weapons certification and assessment. LANSCE's nuclear weapons research supports:

1) ***Robust weapon surveillance*** - data to enable diagnosing and predicting aging-related phenomena in stockpile weapons,
2) ***Science-based prediction*** - developing the capability to predict weapons performance and the consequences of the aging and manufacturing processes on weapons performance, and
3) ***Repair and remanufacture*** - data enhancing the capability to remanufacture, repair, and revalidate stockpile weapons.

## NATIONAL ENERGY SECURITY

*The future of LANSCE is key to developing national energy security.* LANSCE enhancements will provide a new capability for the production of fast neutrons of sufficient intensity to research and optimize the next generation of materials and fuels necessary to deploy advanced fission systems for U.S. energy security. The LANSCE Materials Test Station (MTS) will achieve neutron intensity levels equivalent to a 100 MW fast-flux reactor. This materials irradiation capability, in concert with the post irradiation examination capabilities, will provide necessary data for the validation of materials simulation models enhancing science-based prediction of materials behavior. This capability will be an integral component of the fast reactor development program as the nation's premier source of high-intensity fast neutrons. In addition, the LANSCE-MTS will provide a world-class capability to develop the advanced materials needed for fusion systems.

## BASIC SCIENCE

*The future of LANSCE is integral to the scientific vitality of Los Alamos National Laboratory.* The need for new research tools addressing national defense and national security is growing dramatically. Large-scale user facilities are essential to the materials science and bioscience research enterprise. At LANL, LANSCE's Lujan Center, the Center for Integrated Nanotechnology (CINT), and the National High Magnetic Field Laboratory (NHMFL) form a suite of premier materials science and bioscience facilities creating an environment where researchers pursue leading-edge science in materials structure, materials synthesis, nanoscience, structural biology, high magnetic fields and pressure, and the synergies between them. Understanding and designing materials is a scientific grand challenge of international scope, relevant across the nation's and LANL's mission portfolios. LANSCE is positioned to meet these mission challenges by providing unique materials characterization tools, and the finest testing environments (radiation, high-pressure, high-temperature).

LANSCE is also a magnet facility that attracts the research talent required for Laboratory programs and the Laboratory's scientific enterprise—LANSCE user programs attract a large number of the world's foremost students, faculty, and postdoctoral fellows. Over 1000 user-visits were logged during the 2004 run cycle.

The nation's stewardship of nuclear weapons requires Los Alamos to sustain a vibrant research enterprise in the science that underpins weapon performance, including understanding the dynamic behavior of materials, the aging of materials, and the formulation of new materials for their refurbishment, replacement, and production.

In summary, LANSCE is a vital element of science at Los Alamos, within NNSA, and in the nation. Its national security role is clear and important. Its role in sustaining the Laboratory's scientific enterprise is vital. Enhancing LANSCE performance will anchor scientific excellence in materials science, biological science, nuclear science, and nuclear energy technology for decades to come.

## LANSCE FUTURES

Future national missions will require enhanced LANSCE capabilities to support five principal research (or "thrust") areas:

1) ***Proton Radiography (pRad)*:** to meet Stockpile Stewardship Program's (SSP) mission critical requirements for the next decade.

2) ***Weapons Nuclear Science:*** to meet SSP and Homeland Security mission requirements and enable the acquisition and fulfillment of Sandia National Laboratories' Pulsed Reactor program's (SPR) mission.

3) ***Civilian Nuclear Science:*** to enable operation of the Materials Test Station, meeting the needs of nuclear reactor research for future energy security.

4) ***Materials Science and Bioscience:*** to enhance neutron scattering performance at the Lujan Center for understanding the performance and aging of weapons materials, and to support development of the broad spectrum of new materials needed for stockpile stewardship and threat reduction, and to develop a prototype Generation-III long pulse spallation neutron source—NxGens—enabling future materials science and bioscience discoveries.[1]

5) ***Fundamental Nuclear Physics:*** to enable reliable cold and ultracold neutron production at unprecedented intensities and densities, allowing revolutionary new research on cold and ultracold neutrons, neutrinos, and nuclear astrophysics—keeping the U.S. in the forefront of fundamental nuclear physics research.

## ENHANCING LANSCE PERFORMANCE

LANSCE performance enhancements are focused on the future needs of security, defense, and fundamental sciences and include facility enhancements designed to address specific mission requirements for multiple sponsors over the next twenty years. The enhancement strategy is composed of two parts: enhancements to LANSCE facilities that take full advantage of 800 MeV LINAC performance, and upgrades to accelerator energy and power that enable new and significant upgrades to facility performance. A thorough discussion of possible enhancements is provided in *Appendix G: LANSCE Accelerator Improvement and Enhancement Options*.

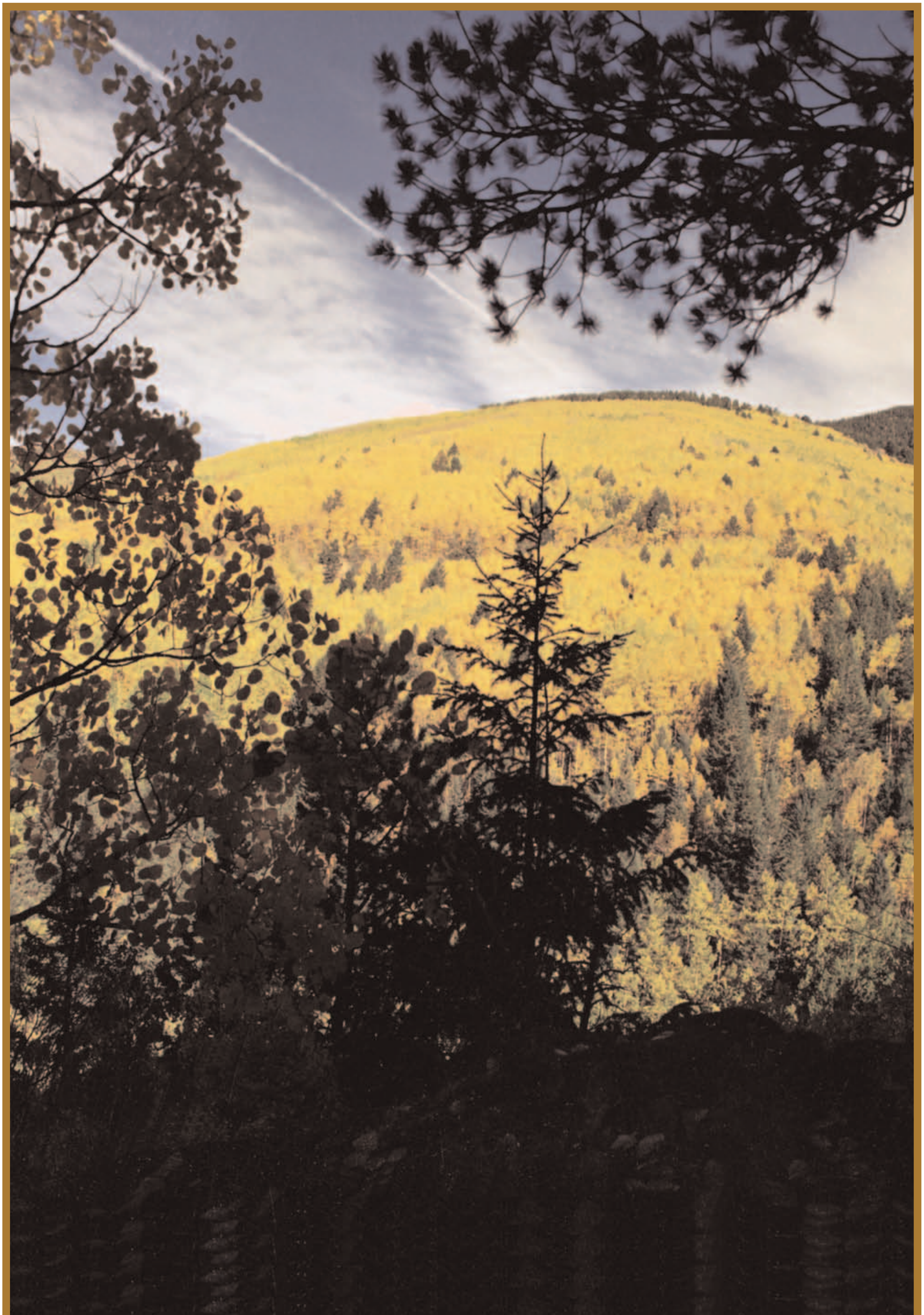
Major benefits of enhancement include:

- ***pRad:*** better imaging at 800 MeV and higher-energy, more intense beams to fully resolve dense, full-scale systems for hydrotesting. The energy enhancement is a function of requirements that are presently under development. Likely energy requirements range from 3 GeV to 20 GeV.
- ***Weapons Nuclear Science:*** production of and measurements on short-lived isotopes for higher-fidelity weapons nuclear data. Enhanced burst production of neutrons for weapon's electronic component testing (SPR mission replacement).
- ***Civilian Nuclear Science:*** improved irradiation capability for materials testing with the MTS—achieving fast-flux reactor performance.
- ***Materials Science and Bioscience:*** upgrading the Lujan Neutron Scattering Center to achieve full scientific utilization with fourteen instrumented flight paths serving 750 users per year. Enabling the NxGens neutron scattering prototype using the long pulse format that will attain unprecedented cold neutron scattering performance.
- ***Fundamental Nuclear Physics****:* several new classes of neutrino sources and best-in-the-world ultracold neutron source for fundamental nuclear physics research.

What follows is a thorough description of the enhancements proposed and their benefits to national security and defense, energy security, and basic science.

[1]The SNS is considered a Generation-II neutron scattering facility and will be the premier thermal neutron scattering facility for at least two decades. The NxGens long pulse structure will enable more energy per pulse on target than SNS, resulting in enhanced performance over SNS for applications utilizing cold neutron scattering.


Pete Nanos, director of Los Alamos National Laboratory, addressing the LANSCE Advisory Board in April 2005.



# Introduction

Kurt Schoenberg, *LANSCE-DO*

# Los Alamos Neutron Science Center

## THE FUTURE MISSIONS

Los Alamos Neutron Science Center's (LANSCE) future capabilities are driven by three principal mission elements:

1) LANSCE will provide critical research facilities and staff to meet the needs of national defense and national security, including research for the stewardship of the future U.S. nuclear deterrent.
2) LANSCE will provide critical research facilities and staff to meet the needs of national energy security.
3) LANSCE will be a cornerstone research facility for scientific enterprise at Los Alamos National Laboratory (LANL) and for the United States.

## REQUIREMENTS

To meet the missions, LANSCE will require infrastructure refurbishment to achieve sustained reliability of its 800 MeV linear accelerator, enhancement of its research facilities, and enhancement of its accelerator. LANSCE refurbishments, captured within the LANSCE refurbishment project (LANSCE-R),[1] are designed to meet operational reliability requirements for the next two decades. The capability enhancements of LANSCE, discussed in this report, are designed to meet the evolving mission research requirements through at least 2025.

## THE LANSCE FACILITY

LANSCE is a complex of multi-disciplinary experimental facilities located at Los Alamos National Laboratory (see Figure 2, page 18). LANSCE provides extraordinary research capabilities in basic and applied science for national security, defense, and civilian applications. Central to the LANSCE facility is a versatile 800 MeV proton linear accelerator (LINAC) that drives five facilities with unique national research capabilities:

***1)*** ***Proton Radiography Facility (pRad)*** for high-resolution, time-dependent, high-speed proton imaging—a critical capability to interrogate the hydrodynamics phase of a nuclear weapon, and for understanding the dynamic properties of weapon materials under extreme conditions,

***2)*** ***Weapons Neutron Research Facility (WNR)*** for weapon nuclear physics research using the world's most intense high energy neutron source to better quantify the nuclear processes that drive weapon performance,

***3)*** ***Lujan Neutron Scattering Center*** for condensed-matter and nuclear physics research using the brightest pulsed beams of moderated cold, thermal, and epithermal neutrons in the world,

***4)*** ***Isotope Production Facility (IPF)*** that produces proton-rich isotopes for biomedical research and medical applications, and the

***5)*** ***Ultracold Neutron (UCN) Research Facility*** for fundamental nuclear physics research using the world's most intense ultracold neutron source.

***LANSCE is a critical facility for national defense and national security research.*** Current LANSCE-based research and facilities are strongly tied to the requirements for maintaining and certifying the U.S. nuclear deterrent. All three National Nuclear Security Administration (NNSA) laboratories (Sandia National Laboratories, Lawrence Livermore National Laboratory, and LANL) and the UK Atomic Weapons Establishment (AWE) need and use LANSCE facilities to effectively address scientific and technical issues necessary for weapons stewardship.

In the future, LANSCE research will continue to address issues from the three major components of NNSA's Stockpile Stewardship Program (SSP):

***1)*** ***Robust weapon surveillance*** **-** data to enable diagnosing and predicting aging-related phenomena in stockpile weapons,

***2)*** ***Science-based prediction*** **-** developing the capability to predict weapons performance and the consequences of the aging and manufacturing processes on weapons performance, and

***3)*** ***Repair and remanufacture*** **-** data enhancing the capability to remanufacture, repair, and revalidate stockpile weapons.

LANSCE enhancements will allow the NNSA to meet specific stockpile stewardship requirements and challenges over the next two decades. LANSCE is also strategically poised to address the unique technological challenges in national security facing the Department of Homeland Security.

*LANSCE enhancements will allow the NNSA to meet specific stockpile stewardship requirements and challenges over the next two decades.*

***LANSCE is a critical facility for national energy security research.*** LANSCE will provide a new capability for the production of fast neutrons of sufficient intensity to research

[1]Proposed Line Item LANSCE Refurbishment Project, Lisowski, P. W., Los Alamos National Laboratory, LA-UR-04-1350, 2004.

## NATIONAL SECURITY AND DEFENSE SCIENCE: THE STOCKPILE STEWARDSHIP PROGRAM

LANSCE is essential to the National Nuclear Security Administration's Stockpile Stewardship Program (SSP). LANL, Sandia National Laboratories, Lawrence Livermore National Laboratory, and the Atomic Weapon Establishment (UK) use LANSCE to address stockpile issues in weapons science and Directed Stockpile Work.

Over the past half-decade LANSCE research generated:

1) Data underpinning the certification of B61 performance for specific Stockpile to Target Sequence (STS) requirements,
2) Nuclear data critical to re-baseline the performance of the W88 primary, and
3) Materials data validating component re-use in the W76 Lifetime Extension Program (LEP).

The major performance drivers of a nuclear weapon include high-explosive detonation and burn, primary implosion, primary burn, radiation transport, secondary implosion, secondary burn, and output effects. Understanding the science of weapons within the context of Quantification of Margins and Uncertainties (QMU*), is necessary to accurately predict weapons performance across the STS environment.

The QMU provides a construct to set the science and data requirements for future stockpile certification. Figure 1 (pg. 16) illustrates how LANSCE research meets the needs of QMU-based science requirements. LANSCE addresses issues across almost all of the major weapon performance drivers. Future research areas and their requirements critical to stockpile stewardship include the following:

***pRad:*** Research utilizing 800 MeV proton radiography will remain critical to stockpile certification. Over the next decade dynamic pRad experiments will require the ability to resolve features with 1 mm accuracy in targets of up to 60 gm/cm$^2$ areal density to resolve present technical gaps and uncertainties in weapon science. Specific research areas include:

- *Investigating the behavior of high-explosive (HE) materials, including the equation-of-state (EOS) and constitutive properties affected by aging,*
- *Assessing the effect of aging on stockpile materials and associated performance,*
- *Resolving uncertainties in HE burn and dynamic material properties, and*
- *Employing scaled experiments to quantify the hydrodynamics phase of a weapon and test performance models.*

Future SSP requirements are evolving to include validating the performance of engineered "full-scale" weapon components using pRad at high spatial and high temporal resolution. Full-scale-hydro-tests using surrogate materials require additional capabilities, which are met by having a 20 GeV-class proton facility. The evolving mission will likely require a 20 GeV-class pRad capability to meet future SSP mission needs in the 2010 – 2025 time frame.

***Weapons Nuclear Science:*** Uncertainties in nuclear data drive uncertainties in code predictions of weapon performance metrics. Over the next decade improvements in nuclear performance modeling by Advanced Simulation Computing (ASC) codes will require reduction in nuclear data uncertainties. This in turn will require cross-section data on short-lived isotopes that heretofore have not been possible. Specific research areas include measuring:

- *Neutron cross-sections for actinides and radiochemical isotope chains (including short-lived isotopes) to interpret archival underground nuclear tests, and validate weapons performance predictions (yield and actinide inventories), and*
- *Principal fission and fusion cross-sections of nuclear fuels, including reaction products, to accurately quantify energy production and weapons performance.*

***Materials Science:*** Understanding the dynamic behavior of stockpile materials, the aging behavior of stockpile materials, and the ability to engineer modern materials into stockpile weapons for their future refurbishment, replacement, and production are requirements for future certification. Using the combined capabilities of pRad and cold neutron scattering at the Lujan Center, LANSCE will:

- *Determine the constitutive properties of weapons materials, such as plutonium and beryllium, at high temperature and high pressure,*
- *Assess the effect of aging on stockpile materials and performance,*
- *Measure the EOS of stockpile metals, polymers, and high-explosives,*
- *Investigate significant findings on an expedited basis, and*
- *Quantify manufacturing issues, like changes in fabrication.*

*QMU is a methodology for future weapons certification and is based on the reduction of uncertainty through scientific understanding.

and optimize the next generation of materials and fuels necessary to deploy advanced fission systems for U.S. energy security. The LANSCE Materials Test Station (MTS) will achieve neutron intensity levels equivalent to a 100 MW fast-flux reactor. This materials irradiation capability, in concert with the post irradiation examination capabilities, will provide necessary data for the validation of materials simulation models enhancing science-based prediction of materials behavior. This capability will be an integral component of the fast reactor development program as the nation's premier source of high-intensity fast neutrons. In addition, the LANSCE-MTS will provide a world-class capability to develop the advanced materials needed for fusion systems.

*Understanding materials behavior in intense radiation environments is critical to developing next-generation fission and fusion energy systems and, therefore, to national energy security.*

***LANSCE is a cornerstone research facility for LANL's scientific enterprise***. LANSCE is a proven magnet for research talent in scientific areas important to the weapons program and the Laboratory's scientific enterprise. For example, the user programs at WNR and Lujan Center attract a large number of students, faculty, and postdoctoral fellows with over 1000 user-visits logged during the 2004 run cycle. Since 1972, LANSCE facilities have generated 287 graduate student PhDs. An estimated ten percent of Laboratory-wide technical staff joined LANL as a result of their LANSCE-based research.

Research on condensed-matter physics and materials science crosscut the mission requirements for defense and the Laboratory's scientific enterprise.[2]

- Addressing principal issues for the stewardship of nuclear weapons entails understanding the dynamic behavior of materials, the aging behavior of stockpile materials, and the ability to engineer modern materials into stockpile weapons for their future refurbishment, replacement, and production.
- Understanding materials behavior in intense radiation environments is critical to developing next-generation fission and fusion energy systems and, therefore, to national energy security.
- Understanding and designing materials at the nanoscale is a 21st Century scientific grand challenge of international proportion.
- Bioscience, representing the greatest growth in materials research in the past decade, is critical to the broader national security agenda.

*LANSCE is a "destination for scientific excellence" attracting premier staff and the best scientific students– the next generation of LANL scientists.*

Large-scale user facilities are essential to the materials science and bioscience research enterprise. At LANL, the Lujan Center at LANSCE, the Center for Integrated Nanotechnology (CINT), and the National High Magnetic Field Laboratory (NHMFL) form a suite of top-of-the-line materials science and bioscience facilities. Together they provide materials science, bioscience, nanoscience, high magnetic fields and pressure science, and facilitate the synergies between them.

Materials science and biological science need new tools with greater power and acuity. LANSCE has a unique and propitious opportunity to develop several critical next-generation capabilities anchoring scientific excellence in materials and biological science for decades to come. A prototype long pulse spallation source—NxGens—will explore the promise of Generation-III neutron scattering capabilities. NxGens will overcome the intrinsic limitations of present and planned short-pulse sources, and will anchor 21st Century materials research for basic, weapons, and threat reduction research. The LANSCE-MTS will provide the nation with a unique capability to design and test materials with fast-flux neutron irradiation to develop future nuclear energy systems.

*Understanding and designing materials at the nanoscale is a scientific grand challenge of international scope.*

## LANSCE FUTURES WORKSHOPS

In 2005, the Laboratory and the University of California sponsored a series of workshops designed to facilitate discussion and debate about LANSCE's proposed refurbishment, and to recommend what enhancements were needed to meet the current, and future, missions. Key representatives from nuclear science, nuclear energy, materials science, condensed matter, bioscience, industry, and academia were invited. The participants carefully considered the costs and benefits of a myriad of possible scenarios, taking into account economic, political, scientific, technological, and social considerations.

In short, the participants unanimously endorsed the immediate investment in LANSCE's refurbishment, recognizing that refurbishment is needed to guarantee LANSCE's productivity and reliability, and providing LANSCE the capability for continuing to serve the nation's needs for the next fifteen to twenty years. Furthermore, the participants recommended that refurbishment be linked to LANSCE's future enhancement.

[2]Note that, as discussed in the following chapters, the capabilities enabled by the major requirements, deriving from the weapons program and materials science, also enable other leading-edge capabilities in fundamental physics.

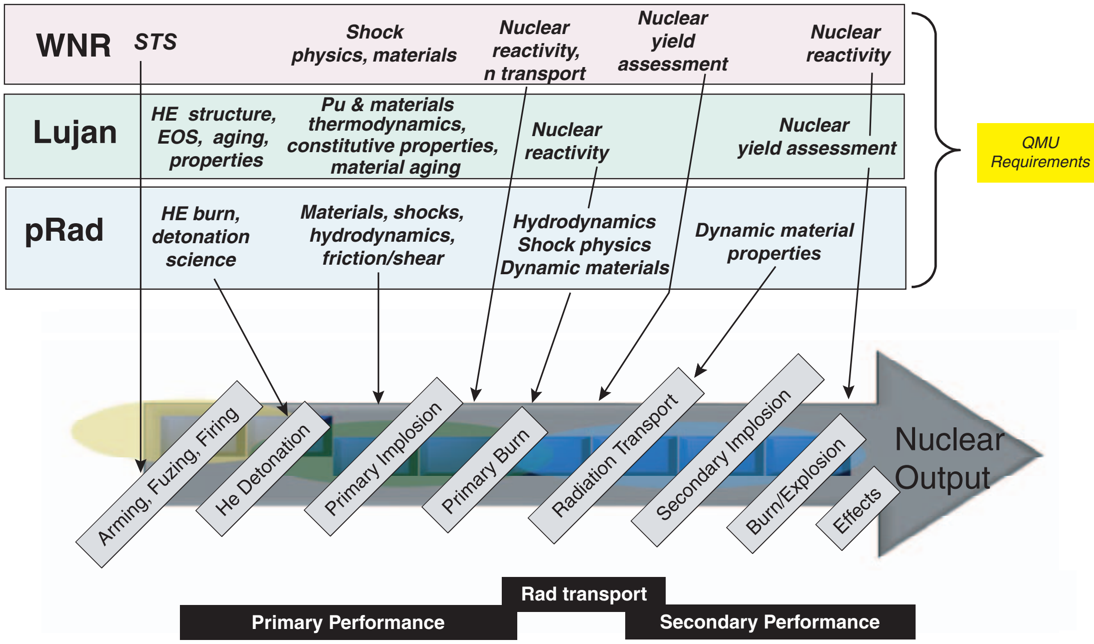



**Figure 1.** LANSCE capabilities uniquely address the science-based predictive capability necessary for present and future weapons certification.

## CIVILIAN NUCLEAR SCIENCE: ENABLING THE NEXT GENERATION OF NUCLEAR POWER PRODUCTION FOR NATIONAL ENERGY SECURITY

*"The expansion of nuclear energy is recommended as a major component of our national energy policy. Key elements of this goal are the Generation-IV and Advanced Fuel Cycle Initiatives."*

– *From Energy for a New Century, U.S. National Energy Policy, 2004.*

To support the missions of the Generation-IV and Advanced Fuel Cycle Initiatives the U.S. needs a new fast neutron irradiation capability to prove the performance of new fuels and advanced materials: a Materials Test Station (MTS) using 800 MeV protons coupled with a spallation neutron production target. The LANSCE-MTS will benefit from enhancements to accelerator performance through increased neutron production. The MTS's capability, in concert with the post-irradiation examination capability, will provide necessary and timely data for the validation of materials simulation models enhancing our science-based prediction of materials behavior.

*This capability will be an integral component of the fast-reactor development program as the nation's premier source of high-intensity fast neutrons, and supports the schedule for the introduction of a demonstration reactor in the 2020 timeframe. In addition, the LANSCE-MTS will provide the capability to develop the advanced materials needed for fusion systems, and generate nuclear isotopes for medical research and defense applications.*

A summary of the relevent workshop reports is provided at the conclusion of Chapters 2 through 5.

In looking to the future, it is critical that LANSCE continue its position at the forefront of research in scientific areas that are both vibrant and relevant to the Laboratory's missions.

*A prototype long pulse spallation source—NxGens—will explore the promise of Generation-III neutron scattering capabilities. NxGens will overcome the intrinsic limitations of present and planned short-pulse sources, and will anchor 21st Century materials research for basic, weapons, and threat reduction research.*

## FUTURE LANSCE CAPABILITIES

Meeting future mission requirements is the driver for LANSCE's enhancement strategy. The strategy is built upon five principal scientific thrust areas that support the missions:

1) Advanced radiography with protons (pRad)
2) Weapons Nuclear Science (WNR)
3) Civilian Nuclear Science for national energy security, including the Materials Testing Station (MTS)
4) Materials Science and Bioscience
5) Fundamental Nuclear Physics

Each thrust area requires specific facility enhancements to meet the missions.

## MEETING THE MISSIONS: IMPROVING LANSCE CAPABILITIES

The LANSCE-R project will ensure sustainable and reliable facility performance at 800 MeV for decades. LANSCE-R will also improve facility performance by doubling the current injected into the drift tube LINAC (DTL), effectively doubling the protons per pulse delivered to pRad and WNR. This improvement also increases the maximum current to the Lujan Center spallation target with a concomitant increase in neutron intensity.

Enhancements beyond LANSCE-R are focused on the needs of security, defense, and fundamental science over the next two decades. The enhancement strategy is composed of two parts—enhancements to LANSCE facilities that achieve full 800 MeV capability and upgrades to accelerator energy or power that enable new and significant improvements to facility performance. Major elements and benefits of the enhancements are summarized below.

### Enhancements to Fully Realize 800 MeV Performance

***pRad:*** Higher quality imaging and experimental facility improvements to address present technical gaps and uncertainties in weapons science. Includes:

- High-quantum efficiency charge-coupled device (CCD) detectors improve data fidelity for dynamic experiments.
- A powder-driven gas gun provides the capability for new planar hydro-shock experiments.
- An electromagnetic pulsed-power driver enables pressure-tailored, convergent hydro and shock experiments.
- Dynamic experiments with twenty pounds of HE drive.

***Weapons Nuclear Science:*** Production and measurements on short-lived isotopes for higher-fidelity nuclear data. Enhanced burst production of neutrons for weapon electronic component testing. Includes:

- The upgraded Germanium Array for Neutron Induced Excitations (GEANIE) detector array at WNR increases gamma-ray efficiency and enables small-sample cross-section measurements on unstable nuclei.
- The upgraded Fast-Induced Neutron Gamma-ray Observer (FIGARO) detector array at WNR improves fission neutron spectra measurements with actinides.
- Building a facility for preparing unstable radioactive samples produced at the Isotope Production Facility (IPF) and MTS enables research with short half-life isotopes.
- Improvements to Proton Storage Ring (PSR) intensity and PSR to WNR beam transport.

***Civilian Nuclear Science:*** Enhanced irradiation capability for the MTS that shortens the time necessary to qualify materials and fuels. Includes:

- Upgrading the LINAC to accelerate a peak current of 21 mA and to accommodate an increase in Radio Frequency (RF) duty factor will allow operation at high-energy-per-pulse (33.6 kJ) effectively doubling the power to the MTS.

***Materials Science and Bioscience:*** Upgrading the Lujan Center to achieve full scientific utilization, fourteen fully instrumented flight paths, and 750 user visits per year.[3] Includes:

- Developing Flight Path 8 with the Los Alamos Pressure Temperaure Research Online Neutronmeter (LAPTRON) high pressure instrument.
- Developing Flight Path 11b with a new inelastic scattering instrument.
- Completing the Flight Path 13 IN500 inelastic instrument.
- Fully refurbishing old instruments to state-of-the-art standards.

[3]Area Development Plan: LANSCE Planning Area, Lisowski, P. W., Los Alamos National Laboratory, LA-UR-03-1771, 2004.

## LOS ALAMOS NEUTRON SCIENCE CENTER'S LINEAR ACCELERATOR

A schematic of the present LANSCE 800 MeV linear accelerator (LINAC) is shown in Figure 2. Ion sources, placed in Cockroft-Walton generators, produce $H^+$ and $H^-$ beams. The beams are bunched into a 201 MHz time structure and merged (as well as chopped in the case of $H^-$) in a low-energy beam transport system at an energy of 750 keV. The beams are injected into a four-tank 201 MHz drift tube LINAC (DTL) and accelerated to 100 MeV.

The 100 MeV $H^+$ beam is presently shunted to the Isotope Production Facility (IPF) producing proton-rich isotopes for medical research and, in the future, radiochemical isotopes for National Nuclear Security Administration defense program nuclear data measurements.

The 100 MeV $H^-$ beam is matched transversely to an 805 MHz side-coupled LINAC (SCL) by elements in the transition region. The SCL accelerates the beam to 800 MeV in forty-four modules. The 800 MeV beam emerging from the SCL consists of 620 microsecond "macropulses" delivered at up to 120 Hz. The flexibility afforded by this temporal pulse structure allows the LINAC to serve multiple experimental sites and applications. The beam is directed by way of a switchyard and kicker magnet to the experimental areas including pRad, Ultracold Neutron (UCN), Weapons Neutron Research (WNR), and the Proton Storage Ring (PSR). The PSR pulse-compresses the 620 microsecond macropulse into a 250 nanosecond burst containing 4 x $10^{13}$ protons. PSR to WNR transport is also possible for intense neutron irradiation applications.

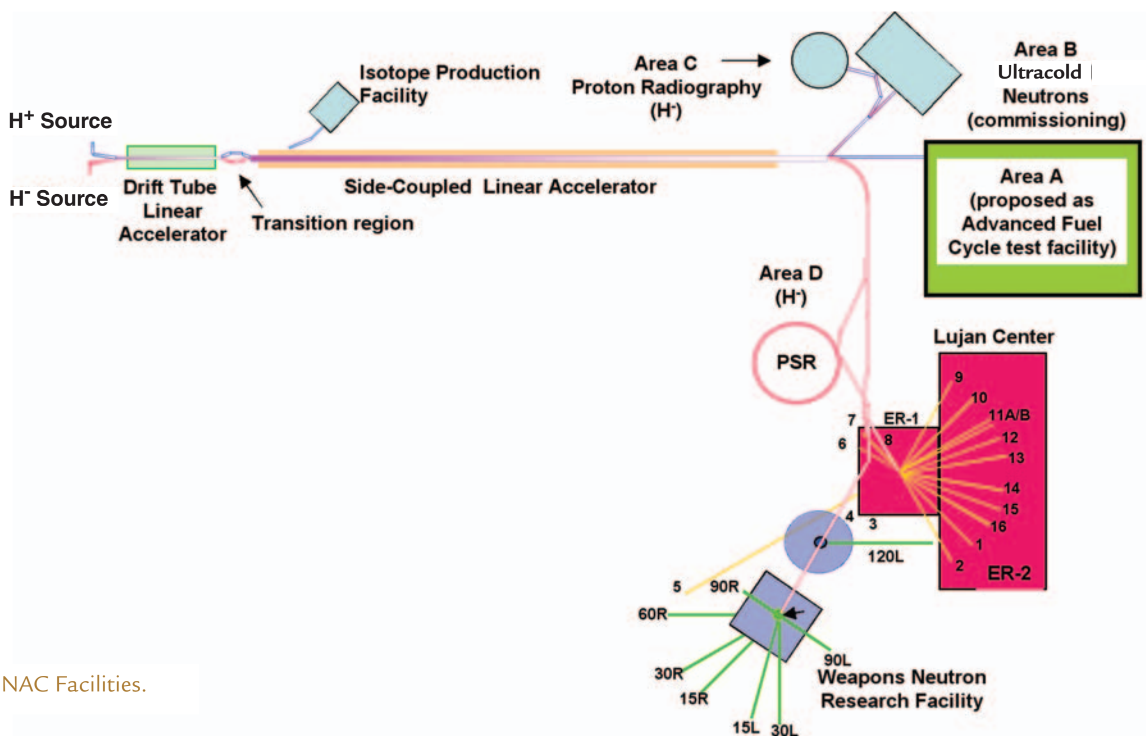



**Figure 2.** LANSCE-LINAC Facilities.

- Investing in experimental infrastructure for sample environments.
- Building a sample preparation laboratory.
- Building a research center including offices, guesthouse, conference facilities, and other facility improvements, to accommodate 750 users per year.
- Building a neutron computation center with visualization facilities.

Demonstrating a next generation (NxGens) neutron scattering flightpath using the long pulse spallation source (LPSS) technique. Includes:

- Modifying the MTS target station to enable a prototype NxGens flight path for Generation-III neutron scattering research. The NxGens approach is a cost-effective strategy to complement the capability of the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory while providing an upgrade path to exceed SNS performance.
- The RF power upgrade. The NxGens prototype will operate with 660 kW of spallation power at 20 Hz for research and development. For short-wavelength high-resolution applications, such as diffraction and strain analysis, NxGens will perform at roughly the same level as the Lujan Center. However, for cold neutron experiments most relevant to soft-matter, nanomaterials and biomolecular science, such as small angle neutron scattering (SANS), reflectometry, protein crystallography neutron spin-echo (NSE) spectroscopy, and low or variable resolution spectroscopy, the prototype NxGens facility will achieve comparable performance to the full power SNS. The NxGens prototype also prepares the path for a significant power upgrade at LANSCE that fully delivers the capability of Generation-III neutron scattering science.
- Installation of the MTS. Enables a high-intensity ($10^6$ per second) muon spin resonance flight path for materials and condensed-matter science.

***Fundamental Nuclear Physics:*** Fully exploiting the ultracold neutron source.

## Beyond 800 MeV: Enhancing Accelerator Power or Energy

LANSCE provides great flexibility to meet future mission requirements through power or energy upgrades tailored to specific program and customer requirements.

One potential enhancement is to upgrade the 800 MeV LINAC to 3 GeV and 6 MW of total beam power for neutron production applications. This option would provide 2.5 MW of cold neutron production at 20 Hz for a NxGens facility, delivering full Generation-III capabilities in neutron scattering research.[4]

The impact of neutron scattering on materials science is reviewed in *Chapter 2: Neutron Scattering: Enabling Materials Science and Bioscience Research at Los Alamos National Laboratory,* and new opportunities enabled by the NxGens are identified across the mission portfolio, including nuclear weapons, threat mitigation, energy security, and basic science. Neutron scattering addresses the scientific grand challenge known as “structure-property relationships in materials.” The NxGens source is needed to meet this challenge; the long pulse format enhances the performance of scattering instruments that measure large-scale morphologies and low-energy excitations. As such, the NxGens addresses both long-standing problems with respect to weapons materials and a host of emerging problems regarding soft materials.

The 800 MeV LINAC provides an expeditious and cost-effective injector for an enhanced energy option for pRad. The pRad requirement for a 20 GeV-class accelerator is driven by the classified results of static experiments performed using the 24 GeV and 7.5 GeV beams from the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory. These experiments showed that 20 GeV is required to measure hydrodynamic processes for full-scale hydro-testing on the largest stockpiled systems. Building on LANSCE-R improvements will save an estimated $100M of project cost for a 20 GeV-class system over building and commissioning a “green-field” facility.

## SUMMARY

Today, LANSCE proudly stands as a cornerstone science facility that serves the security and defense missions of the U.S., the NNSA, and LANL by:

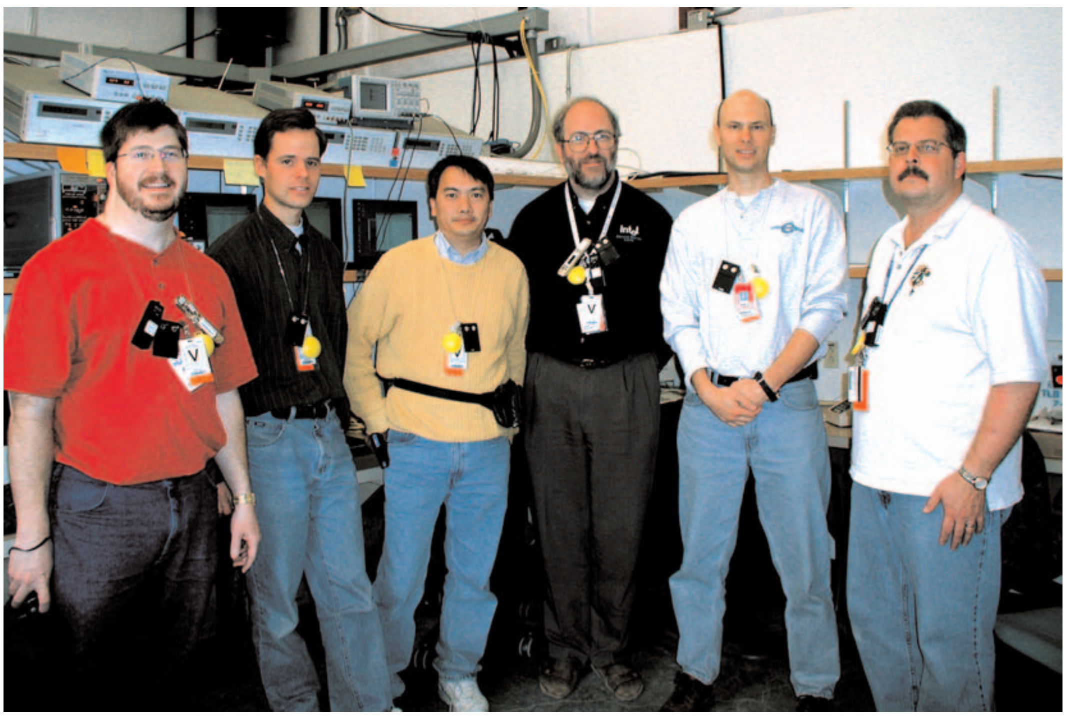
- *Achieving scientific excellence in disciplines critical to the Laboratory’s mission,*
- *Addressing “mission-critical” needs of stockpile stewardship through experimental research that validates predictive tools and models and addresses issues of weapons performance and certification,*
- *Operating premier national user facilities in proton radiography, neutron scattering, and basic and applied neutron science to address important scientific and weapons physics issues, and*
- *Attracting “best-in-class” scientific and engineering talent to LANL through research excellence, its academic culture, and extensive collaborations.*

[4] The performance of this high-power NxGens station will exceed by a large margin that of SNS in long-wavelength (cold) neutron applications, and will be competitive to SNS in most other neutron scattering applications.

Future LANSCE enhancements will secure the capabilities necessary for maintaining the U.S. nuclear deterrent over the next two decades, and provide a world-class "destination for scientific excellence." LANSCE will remain at the forefront of condensed-matter physics, materials science, nanoscale material design, nuclear energy development, structural biology, and nuclear science.

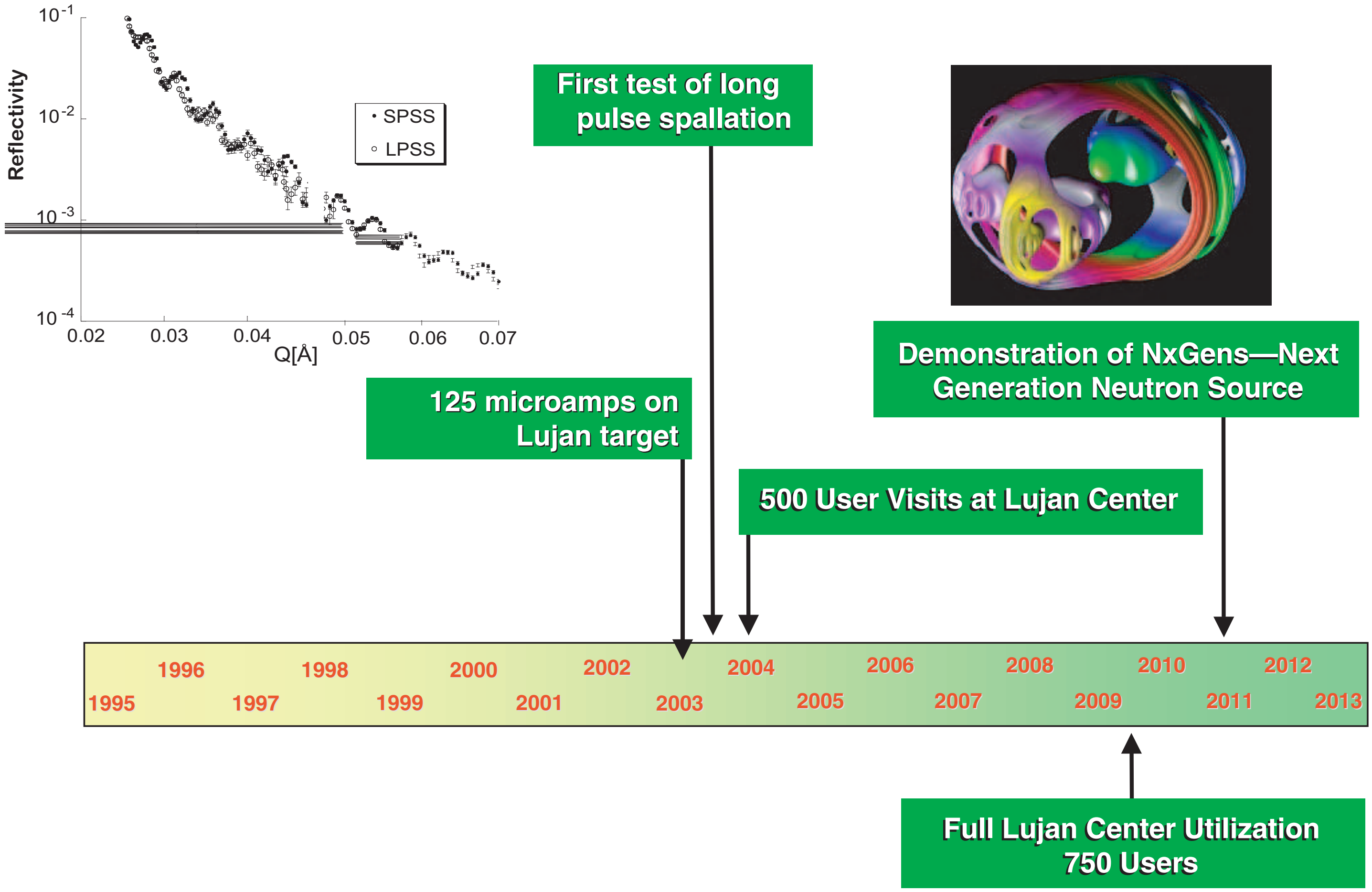
*National defense research, including stewardship of the U.S. nuclear deterrent, national energy security research, and keeping LANL a vibrant, premier cornerstone research facility are the drivers for an evolutionary enhancement strategy for the future of LANSCE.*

LANSCE enhancements, and how they will enable LANL to meet future missions, are further elucidated in the five chapters that follow.



**LANSCE provides premier research facilities for academic and commercial users, like this team from Intel.**

## FUTURE NEUTRON SCATTERING AT LANSCE MUST REACH FOR NEW CAPABILITY FOR THE COMMUNITY



# Chapter 1

## Proton Radiography *and* Physics Certification *of* Nuclear Weapons Primaries

John Hopson, *X-4*
Jeff Goettee, *ISR-5*

THE PROTON RADIOGRAPHY'S HIGH-EXPLOSIVE CHAMBER UNDERGOING ROUTINE MAINTENANCE

# Proton Radiography and Physics Certification of Nuclear Weapons Primaries

## ABSTRACT

There is a complex interplay of physics phenomena that must be tightly controlled for nuclear weapons to work with high reliability. As weapons age, or as it becomes necessary to make engineering changes to the warhead to ensure its continued safety and reliability, it becomes crucial to accurately assess the impact of the change to the weapon's nuclear performance. Improvements to LANSCE's proton radiography detectors, magnetic optics, and dynamic testing facilities are required to produce the quality radiographs required to meet the missions.

## INTRODUCTION

Los Alamos National Laboratory, in collaboration with other national laboratories, developed and successfully applied proton radiography (pRad) to mission requirements of the Stockpile Stewardship Program (SSP). Proton radiography is a powerful tool for elucidating basic principles of how nuclear weapons work. There are two phases in the functioning of a modern nuclear weapon: the hydrodynamic phase and the nuclear phase. In the hydrodynamic phase, which lasts a few tens of microseconds, the mechanism of the primary is driven by a charge of high-explosive. This is sufficient to compress the fissionable plutonium into a highly supercritical configuration. The resulting nuclear fission energy release leads to the nuclear explosion phase, which produces many kilotons of TNT equivalent energy. Because modern weapons are highly tuned to provide great efficiency in yield-to-weight, and to minimize usage of nuclear materials, changes to a weapon's nuclear performance are very sensitive to deviations in the hydro-phase behavior.

Proton radiography is arguably the most valuable single tool available to interrogate the hydrodynamic phase of a weapon. Many physics regimes become operative as the hydro-phase proceeds. These include the initiation and detonation of the chemical high-explosive, the complex response of the metal components to intense shock waves, the extremely high-rate deformation and compression of the fissionable components during the supercritical assembly, and the fundamental hydrodynamics and hydrodynamic instabilities that are driven by these extreme conditions. For each condition it is necessary to develop and validate explicit hydrodynamic physics models that can be implemented in new simulation computer codes (from the Advanced Simulation Computing codes program [ASC]), and which capture with high accuracy the critical behaviors. These models are the main drivers for hydro-experimental data requirements. There are many diagnostic tools developed to assess hydrodynamic behavior; most rely on surface measurements and are unable to interrogate the critical state variables and stress-strain response in the interior of the hydro-components. Modeling depends on accurately capturing the time evolution of the hydrodynamics on a microsecond time scale. Proton radiography, with its ability to penetrate and accurately imagine the interior of highly compressed components, as well as its highly flexible and precisely recordable pulse format, is uniquely suited to providing the necessary data for weapon certification codes and models.

The range of data obtainable from pRad is dependent on the energy of the beam, and the number of protons in each radiographic pulse. LANSCE's current 800 MeV energy of pRad provides most of the fundamental, early-time shock behavior data of weapons materials. There is also the ability to investigate generic, integral hydrodynamic behaviors relevant to the weapon's hydro-phase.

*Proton radiography, with its ability to penetrate and accurately imagine the interior of highly compressed components, as well as its highly flexible and precisely recordable pulse format, is uniquely suited to providing the necessary data for weapon certification codes and models.*

***Sustainability***
It is crucial that the current LANSCE pRad capabilities be sustainable to meet the mission of the Stockpile Stewardship Program. Sustainability for the pRad program is captured in the LANSCE-R project.

***Enhancements***
The range of experiments and quality of the data needed to meet future missions will be significantly enhanced by investing in upgrading LANSCE's dynamic testing facility. This upgrade is captured by the LANSCE enhancement strategy at 800 MeV.

***Maximize pRad Capabilities***
Should the mission require pRad experiments to quantify the complete hydro-phase of a weapon, and maximize the ability to certify the stockpile without resorting to nuclear tests, it will be necessary to increase both the beam energy and the protons per pulse of the pRad facility to 20 GeV and 100 billion protons per pulse. This upgrade is captured by the LANSCE enhancement strategy beyond 800 MeV.

LANSCE pRad enhancements allow validating the science within the computer models, and verify the integrated codes that predict performance of fully engineered systems necessary for the final certification process. These requirements may drive the need for increasing the beam energy and the proton flux. Details of the experiments to be performed at 800 MeV and at 20 GeV follow.

*Should the mission require pRad experiments to quantify the complete hydro-phase of a weapon, and maximize the ability to certify the stockpile without resorting to nuclear tests, it will be necessary to increase both the beam energy and the protons per pulse of the pRad facility to 20 GeV and 100 billion protons per pulse. This upgrade is captured in LANSCE enhancement strategy.*

## BACKGROUND

In general, transmission radiography is accomplished by measuring the transmission of a penetrating beam through an object and using the beam-attenuation to measure the areal density profile (thickness) of the object. Typically, this information is used to quantitatively determine the internal structure of the object. In hydro-testing, a primary from a weapon, in which the nuclear fuel is replaced with a surrogate, is imploded. One goal of hydro-test radiography is to measure densities at "late-times" in the implosion to benchmark numerical simulations used to predict the explosive yield. Until recently, the only diagnostic available for late-time hydro-testing was flash x-ray radiography. With the cessation of underground testing, scientists expended considerable effort to improve x-ray technology, including Dual-Axis Radiographic Hydrodynamics Test (DARHT) facility and the ARIX facility.[1] These facilities produce the largest doses and smallest spot sizes ever achieved. Nevertheless, to answer questions about stockpile performance, at the precision required for long-term stockpile certification, more information is needed. Flash radiography *using protons* will provide the information necessary to meet future certification requirements. The quantative capabilities of proton radiography derive from the ability to focus charged particles.

The current capabilities at LANSCE, using 800 MeV protons, measure generic but critical integral hydrodynamic behavior relevant to the early-time shock behavior within a weapon. These experiments investigate material damage driven by various sources; high-explosives, powder and gas guns, and electromagnetic pulsed power drivers. Materials properties, including strength and failure modes, need to be validated within the ever-evolving ASC computer models. Scaled experiments using test objects, designed to be transparent at this energy, are performed to investigate the interplay between hydrodynamics, test object geometry, and its material content. Energetic materials are also objects of experimentation at this energy. Present experiments at 800 MeV yield equation-of-state (EOS) and detonation evolution information.

Extending proton radiography with a 20 GeV facility, with the authorization bases required for SSP experiments, will add a full-scale hydro-test capability with high-resolution and multiframe imagery.

This capability requires an enhanced dynamic testing facility to provide the containment envelope. It also requires the 20 GeV magnetic optics and fast framing cameras to produce the radiographs. Containment, achieved at the DARHT facility, will be reproduced. The optics are within current technological limits.

*Extending proton radiography with a 20 GeV facility, with the authorization bases required for SSP experiments, will add a full-scale hydro-test capability with high-resolution and multiframe imagery.*

## 800 MeV REQUIREMENTS

### A. Dynamic Materials Science[2]

***Metal Fracture at High Strain Rates***

Understanding fracture ("failure" or "cracking") in the materials in the nation's stockpile is essential to the SSP mission. High-explosives are used to drive metals to failure at high strain rates. Proton radiography is used to track the evolution of fracture. Radiographic movies help solve the questions of failure. Radiography tracks the beginning of material failure, the size distribution of fragments, and the spaces between fragments. This information is fed back into the materials models essential to any hydrodynamics computer code.[3]

***Explosively-Driven Flyers***

Proton radiography is a principal tool to analyse high-explosive-driven, shock-induced damage and melt in metals. These experiments are critical for validation of diagnostics fielded in the subcritical experiments. Future work with metals will be focused on shock-induced damage and phase changes. Proton radiography is an essential part of validation experiments on tin, bismuth, and lead before fielding subcritical experiments.

1) *High-Explosive Experiments.* High-explosive-driven experiments are used to look at shock-induced shear stress; a material failure mode that primary design codes must predict more accurately. Even small-scale experiments that unlock the chronology of stress relief help to benchmark the codes used to predict such behavior. High-explosives are used in flyer experiments. The metal flyer reveals the energy release, and radiography records the metal surface reaction and the pressure waves

[1]Modern Electron Accelerators for Radiography, Ekdahl, C., *IEEE Transactions on Plasma Science 30*, pp. 254-26, 2002.

[2]Personal communication with David Holtkamp, P-22, Los Alamos National Laboratory.

[3]*Nuclear Weapons Journal*, Prestridge, K., Los Alamos National Laboratory, LALP-04-013, pp. 10-12, 2004.

(shocks) within the materials. The density variation within the metal, as well as within the explosive as it expands post-detonation or deflagration, is imaged. This information is compared directly with computational models to refine predictive capability.

2) *Powder-Gun-Driven Experiments.* A gun device is also used to drive flyer plates into a target material. Equation-of-state parameters are extracted by measuring quantities associated with the shocks within the two materials. Powder gun experiments benefit from proton radiography's ability to take multiple images, its excellent spatial and positional resolution, and its penetration of the metals used. Temporal evolution of the interaction of a flyer plate with a target material yields information relevant to the EOS, providing direct measurements of the particle velocity, shock velocity, and shocked material densities.

   The powder gun at LANSCE has the potential to provide new insights into dynamic material properties of metals, polymers, high-explosives and other materials. With the improved 800 MeV beam, potential measurements include:

   a) *Density behind a shock wave.* Density is typically inferred from measurements of other, more fundamental properties, and the resulting propagation of uncertainties can lead to large error bars. A one percent direct measurement of shocked state density will be a significant advancement in shock physics.

   b) *In situ measurement of dynamic damage processes on small length scales.* This will shed light on complex processes such as ductile void nucleation, growth and coalescence, brittle fracture, and shear localization. *In situ* measurements are important for obtaining a detailed understanding of these processes.

   Powder gun-based research easily translates to 20 GeV radiography. The samples will be made larger or made from higher-density materials. Larger samples, either flyers or targets, mean multiple materials will be used simultaneously in side-by-side comparison tests.

3) *Electromagnetic Pulsed Power Driven Implosions*. Pulsed power for implosion geometries can replace the other energetic materials for hydrodynamics experiments. Pulsed power offers a cost effective alternative to high-explosives with the ability to precisely tailor the time dependent pressure applied to implosion.

   Experiments done with pulsed power are usually cylindrical implosions or planar flyers producing the shocks necessary to create spall and dynamic changes. While high-speed photography captures much of the surface phenomenology, radiography provides the internal view of the imploding liner, as well as the metal's interaction with the target. Proton radiography captures the spatial and positional resolutions required, and records the temporal evolution of the phenomenology. The drive energy required for such experiment is within range of even a modest, capacitor-driven system. The experimental load is connected to the driver via a transformer. An electromagnetic pulsed power driver is being developed, and considered part of the dynamic test facility upgrade at pRad.

### B. Damaged Surface Hydro[4]

The Damaged Surface Hydro (DSH) experiments of interest for pRad are intended to examine the behavior of a damaged surface in various hydrodynamic regimes. The experiments are designed with a high-explosive drive in cylindrical geometry. Proton radiography is used to measure the surface properties where spatial and temporal resolution are the key parameters. The cameras, improved by LANSCE and discussed later in this report, improve pRad experiments performed at 800 MeV or at 20 GeV.

### C. Scaled Hydrodynamics

Scaled experiments are used to investigate engineered systems with 800 MeV proton radiography. Many successful dynamically driven experiments have been performed. The series of radiographs yields quantifiable information to verify the predictions of the integrated hydrodynamics codes. Higher energy protons at higher flux will allow the ASC codes to be thoroughly benchmarked, at full scale.

## LANSCE ENHANCEMENTS MEET FUTURE REQUIREMENTS

***Full Utilization of the 800 MeV Capability***

Continuing the stream of weapon-related experiments done at LANSCE with proton radiography is key to the illumination of physical phenomena currently being addressed. Leading-edge experiments with test objects appropriate for 800 MeV energy continue to address questions in hydrodynamics and materials science. These include the phenomena effecting the early-time events of a primary's implosion. Improved, more efficient detectors, and infrastructure improvements to test facilities are needed to meet mission requirements.

Research and development at LANSCE of new charge-coupled device (CCD) cameras for the pRad program increase quantum efficiencies by more than eighty percent. This

[4]Personal communication with Guy DiMonte, X-4, Los Alamos National Laboratory.

represents a four-fold improvement in the data statistics over current pRad detector systems, with a high-frame-rate-format that further enhances the imaging capabilities.[5]

Improved detectors take advantage of CCD cameras with high quantum efficiencies that operate at the megahertz frame rates required by the dynamic experiments. New magnetic optics will improve the intermediate magnifier (3x) within the large 8 cm field of view. Since 800 MeV energy allows only scaled physics-type experiments, the increase in energetic material limits is crucial to the scaled implosion geometries. New dynamic drivers ensure the detection capabilities are fully utilized by expanding the range of possible experiments.

Improving the high-explosive firing operations doubles the authorization basis for the amount of energetic material, giving pRad more experimental flexibility. Other dynamic drivers, including a powder gun for flyer plates and a pulsed power driver for cylindrically imploded geometries, can be added.

*Research and development of new charge-coupled device (CCD) cameras within the pRad program increase quantum efficiencies by more than eighty percent. This represents a four-fold improvement in the data statistics over current pRad detector systems, with a high frame rate format that further enhances the imaging capabilities.*

***20 GeV Maximizes pRad Capability***

Proton radiography is the key diagnostic to interrogate weapon hydrodynamics at late implosion times. Future SSP-based experimentation may require 20 GeV-class capability.[6] The physics and engineering detail of a full or a scaled hydrodynamic test is appropriately imaged and resolved, both spatially and positionally, at this energy level with at least five pulses of 100 billion protons per pulse.

Tests of energy and flux at Brookhaven's Alternating Gradient Synchrotron (AGS), and the accompanying calculations supporting them, show the feasibility of multipulse radiography of such hydrodynamics tests. These same studies describe the required detectors and proton optics required to achieve the sub-millimeter resolution needed for verification of engineering computer models.[7]

*Proton radiography is the key diagnostic interrogate weapon hydrodynamics at late implosion times.*

## SUMMARY

The Stockpile Stewardship Program (SSP) requires validation of the physics and materials science models contained within nuclear weapons codes.

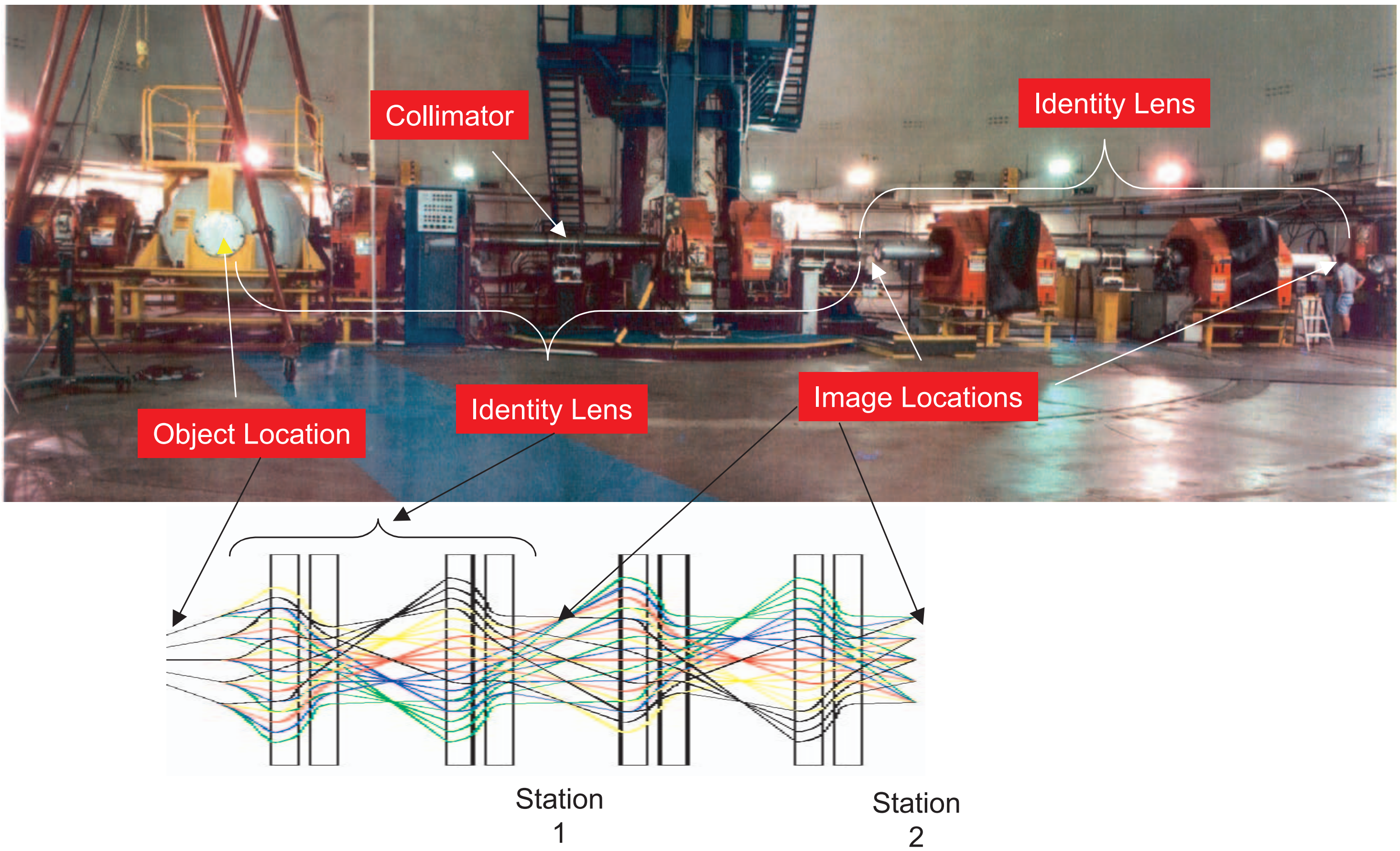
Improvements to pRad detectors, magnetic optics, and dynamic testing facilities are necessary to produce the quality radiographs required to meet the missions now, and in the future.

### PROTON RADIOGRAPHY (pRad)

| Program/Science | Requirements | LANSCE Enhancements |
|---|---|---|
| | | |
| pRad:<br>- Science Validation Experiments<br>- Scaled Hydro-Experiments | <60 $gm/cm^2$ area density with 1 mm resolution. | 800 MeV enhancement meets program requirements to study the critical hydrodynamic behavior and dynamic material properties of a weapon. |
| - Full Hydro-Test Experiments | >5 pulses @ 2 x $10^{11}$ protons/pulse and 200 ns minimum pulse spacing. | 20 GeV-class capability achieves full hydro-test capability for dense, full-scale systems, and future weapons systems certifications. |

[5]Snapshot Hybrid Image Sensor for VSI/NIR/SWIR Ultra High-Speed Imaging, Douence, V., Los Alamos National Laboratory, LA-UR-05-0706, 2005.
[6]Design Feasibility and Cost Estimate for a Single-Axis, Multipulse Proton Radiography Facility, McGill, J., Los Alamos National Laboraory, LA-14126, April 2004.
[7]Some Results From Proton Radiography Experiments 963 Using Alternating Gradient Synchrotron at Brookhaven National Laboratory, Morris, C. L., Los Alamos National Laboratory, LA-UR-04-0074, 2004.

THE pRad FACILITY AT LANSCE FILLS A CRITICAL CERTIFICATION NEED FOR THE WEAPONS PROGRAM



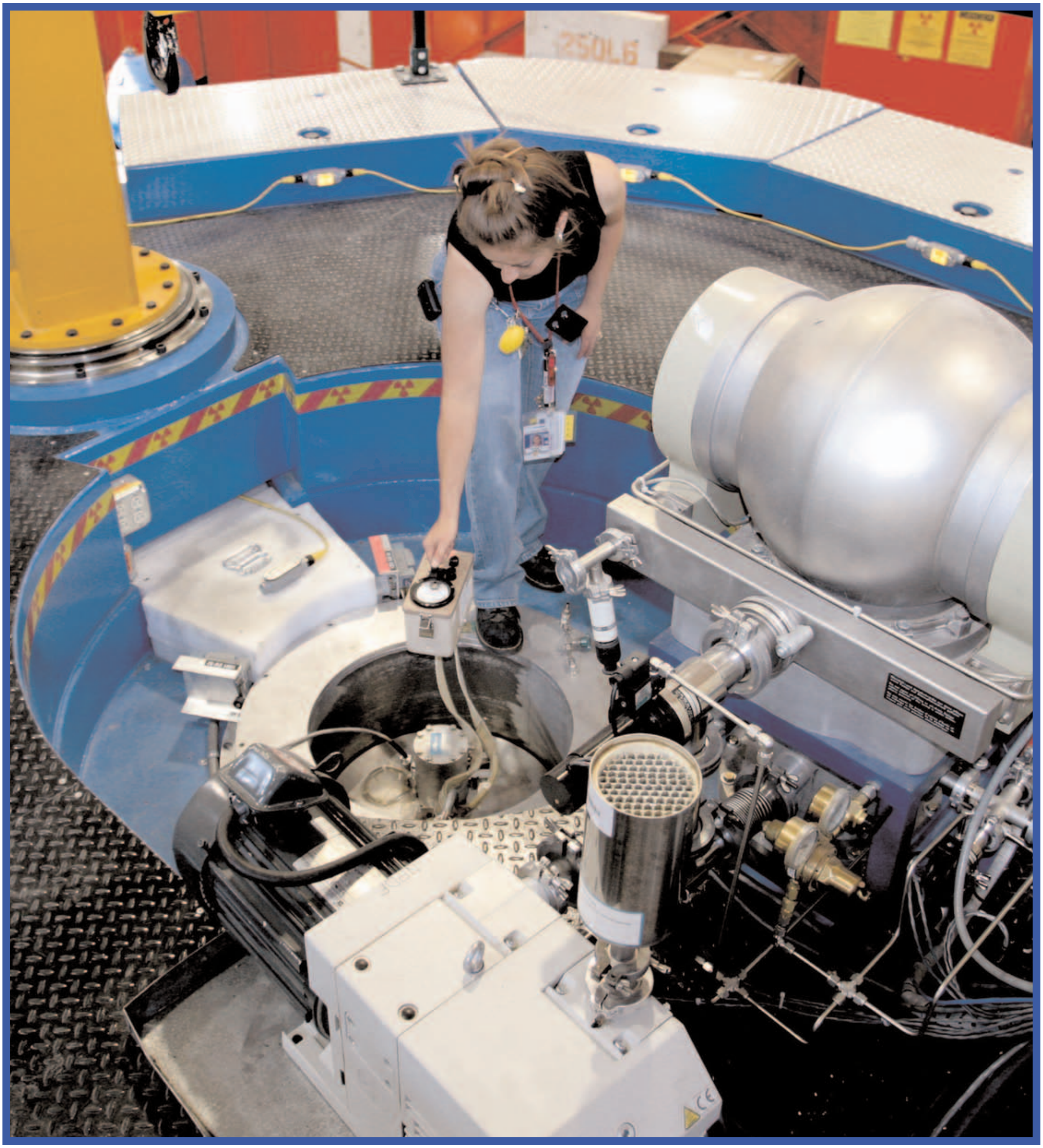

800 MeV proton radiography can effectively radiograph objects with an areal density from 1 g/cm$^2$ up to 60 g/cm$^2$ with a temporal resolution of < 100 ns. Bare resolution (rms) for Station 1:178 $\mu$m and for Station 2:280 $\mu$m.

# Chapter 2

## Neutron Scattering: Enabling Materials Science *and* Bioscience Research *at* Los Alamos National Laboratory

Alan J. Hurd, *LANSCE-LC*
Ferenc Mezei, *LANSCE-LC*
Dale W. Schaefer, *LANSCE-LC and University of Cincinnati*
Paul Langan, *B-2*
Benno Schoenborn, *B-2*
Sunil Sinha, *University of California, San Diego*
Jacob Urquidi, *New Mexico State University*

THE NEUTRON POWDER DIFFRACTOMETER (NPDF) IS A HIGH-RESOLUTION TOTAL-SCATTERING POWDER DIFFRACTOMETER LOCATED AT LANSCE'S LUJAN CENTER



# Neutron Scattering: Enabling Materials Science and Bioscience Research at LANL


## ABSTRACT

Future enhancements will allow LANSCE to meet national defense and national security missions by improving neutron production at the Lujan Neutron Scattering Center and demonstrating a novel next generation—Generation III—neutron source (NxGens) for neutron scattering research. The NxGens, based on a long pulse spallation neutron source, is a cost-effective complement to the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), while providing an efficient path for developing the nation's third-generation spallation neutron source technology.

In this chapter, the impact of neutron scattering on materials science is reviewed and new opportunities enabled by NxGens are identified across DOE's and LANL's mission portfolio, including: nuclear weapons, threat mitigation, energy security, biomedical, industrial, and basic and applied science. Neutron scattering addresses the scientific grand challenge known as "structure-property relationships" in materials. The NxGens is needed to meet this future challenge—the long pulse format enhances the performance of scattering instruments that measure large-scale structure and low-energy excitations. The NxGens addresses both long-standing issues in weapons materials and a host of emerging soft-materials challenges.


## INTRODUCTION

Materials research is enabled by linking experimental, theoretical, and computational tools. Centers-of-excellence in materials science are characterized by complementary capabilities, including large-scale user facilities. Neutron scattering, which probes structure and dynamics across length and time scales relevant to materials properties, is crucial.

LANL will secure enduring leadership in materials science and condensed-matter physics by fostering a rich research environment through indigenous facilities. The synergism of LANSCE's Lujan Neutron Scattering Center with LANL's National High Magnetic Field Lab, the Center for Integrated Nanotechnologies, and Theory Division provides the institutional foundations for scientific leadership in materials science and bioscience research serving national needs.

The impact of neutron scattering is evident across all of materials science. Recent examples include understanding the phase diagram of plutonium (Figure 1), elucidation of the physics of high-temperature super-conductivity, the discovery of water inclusions in DNA structure, and the identification of material failure modes in high-consequence accidents. The growing power of neutron sources and increasing sophistication of associated instrumentation assure an expanding role for neutrons in materials research, particularly regarding the physical and chemical origins of material properties. *(Appendix A: LANSCE Strategic Areas of Neutron Scattering Research*)

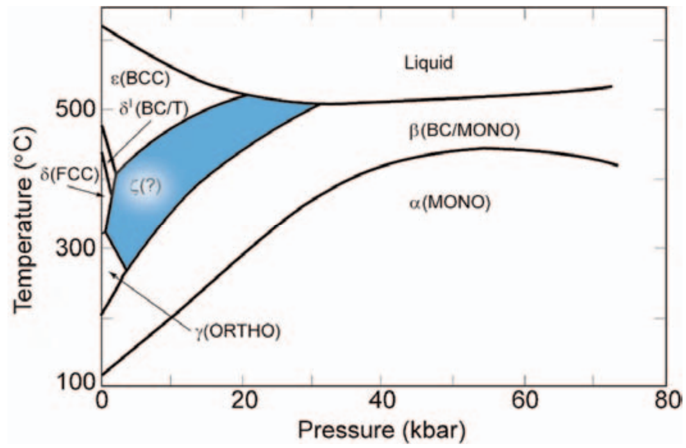



**Figure 1.** The structure of several plutonium phases have been determined by neutron scattering, but the ζ-phase (blue) structure is still unknown. (Lawson, Andrew C., LANL, Personal Communication, 2001)

The rapid data rates of high-intensity sources permit systematic parametric studies on broad families of materials. This emerging paradigm is relevant to the national mission concerning the performance and aging of weapons materials and supports development of the broad spectrum of new materials needed for threat reduction.

## REQUIREMENTS

### Neutrons and Materials: A Primer

Neutron scattering is used to determine where atoms are located and how they move. Elastic neutron scattering provides position information (structure) and inelastic scattering provides information about motion (dynamics). Exactly how the positions and motions of atoms affect properties—strength, compressibility, density, heat capacity, and so on—is one of the grand challenges of science, known as the "structure-property relationship." This connection between the micro- and macro-worlds is a grand challenge not because it is difficult—which it is—but because it promises both top-down understanding of existing materials and bottom-up design of new materials.

Because the neutron scattering power of atoms is isotope-dependent, labeling techniques are widely employed to sort out complex structures, particularly in biomaterials. Hydrogen and deuterium, which are nearly invisible to x-rays, are easily located with neutrons. Hydrogen sensitivity is essential to understanding structure-property relationships in macro-molecules and biological materials. Moreover, the ability to label atoms without changing their chemistry is a unique advantage. Deuterium and hydrogen, for example, differ in scattering cross-sections not only in magnitude but also in sign. Therefore, specific-site deuteration is used to label each part in supramolecular assemblies with great effect.

Since neutrons do not interact with matter via electric forces, many experiments can only be accomplished with neutrons. Neutrons, for example, are deeply penetrating relative to x-rays so can probe inside thick sample environment chambers, or measure deeply buried structures in a bulk high atomic weight material. Neutrons are also magnetic and are particularly well suited for questions of magnetism. The predicted existence of magnetism in plutonium is one such question. If magnetism exists, it is important to the electronic structure and therefore the equation-of-state (EOS) of plutonium.[1] Magnetism may also be relevant to the corrosion properties of plutonium. Neutrons are low-energy probes well matched to the spectrum of excitations that underlie the physics of such phenomena.

Neutron scattering is particularly well suited to meeting the challenge of structure-property relationships. For crystalline materials, the problem appears deceptively simple since bulk properties depend on short-range electronic forces and lattice excitations. Many crystalline materials, however, belie this simplicity. For example, materials with strongly correlated electrons, such as plutonium and high-temperature super-conductors, remain a mystery after decades of research efforts.

Considering its importance in nuclear technology, plutonium remains a dramatic mystery. Plutonium exhibits amazingly complex behavior, and has resisted understanding for over sixty years. Even the structures of some plutonium phases remain uncertain.

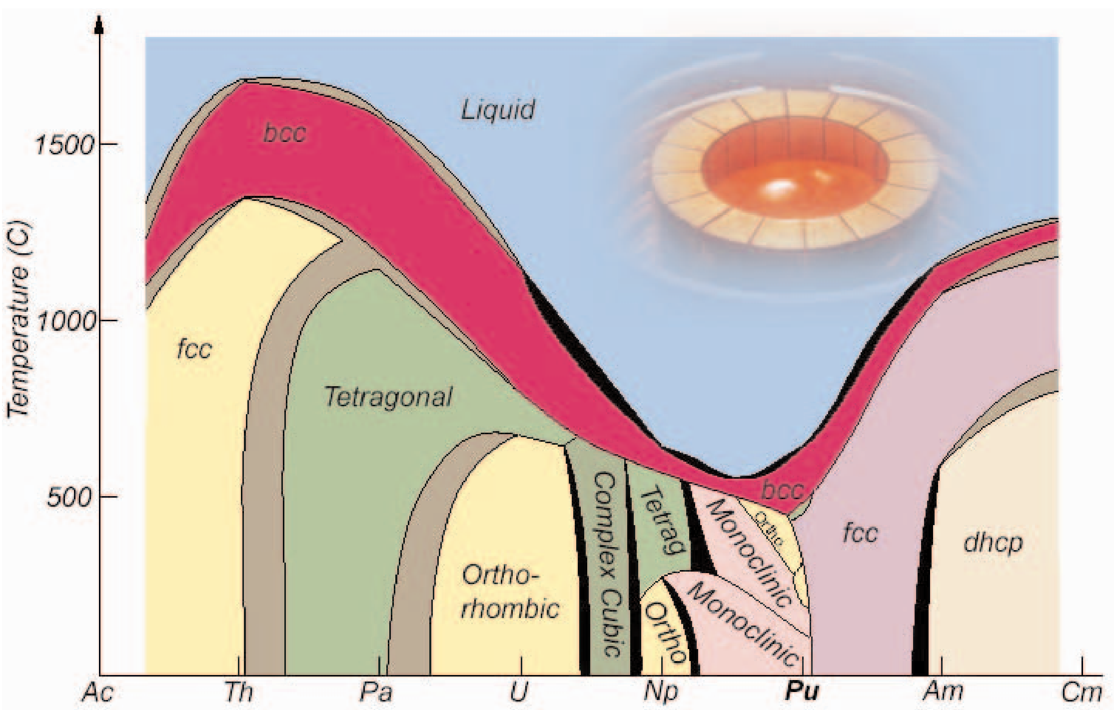



**Figure 2.** Plutonium melts at anomalously low temperature relative to neighboring elements. It exhibits at least seven atomic structures, the δ-phase of which is face-centered cubic (fcc). Ironically, that closest packed form is plutonium's least dense phase. As a result, plutonium is one of the few materials, and the only element, that floats on its own melt (water is a familiar molecular example). The plutonium δ-phase also shrinks when heated. No other element has such complexity, which means that no single element is a suitable surrogate for research.

[1]Stainless-steel is not magnetic and does not corrode, but it does corrode near welds where it has reverted to a magnetic form. It may be that the electronic surface states that participate in corrosion are also responsible for magnetism.

Plutonium melts at anomalously low temperature relative to neighboring elements (Figure 2). It exhibits at least seven atomic structures, the δ-phase of which is face-centered cubic (fcc). Ironically, that closest-packed form is plutonium's *least* dense phase. As a result, plutonium is one of the few materials, and the only element, that floats on its own melt (water is a familiar molecular example). The plutonium δ-phase is also unusual—it shrinks when heated. No other element has such complexity, which means that no single element is a suitable surrogate for plutonium research.[2]

As the need to understand the complexity of materials increases, understanding their properties on larger scales and their dynamics at lower energies becomes more important. It is the trend toward understanding materials complexity that drives the need for a long pulse spallation source. *(Appendix B: LANSCE's Current Capabilities)*

Perhaps the pinnacle of the structure-property challenge is to understand the complexity of biomaterials. Biomaterials are among the coarsest—with inhomogeneities on large scales—and softest of materials classes while having the most complex, emergent properties. Neutron scattering studies of biomaterials, especially using cold neutron techniques, are essential to master the scientific principles by which biomaterials exhibit self-assembly, self-limited growth, healing, and adaptive, emergent properties.

As recognized by the European Spallation Source (ESS) project (2002),[3] the next generation neutron source must emphasize cold neutron flux. The NxGens design, when coupled with state-of- the-art moderators, is the obvious choice for significant national investment. The impact of increased cold neutron flux is not limited to soft-matter. Across the materials science and bioscience disciplines, increased flux is a recurring requirement. These requirements drive the evolutionary, and revolutionary, enhancements proposed for neutron scattering at LANSCE.

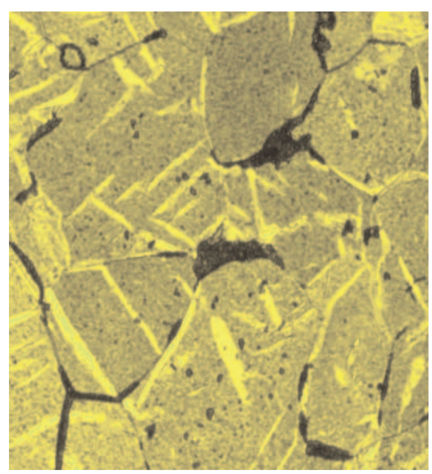
*The pinnacle of the structure-property challenge is to understand the complexity of biomaterials. Biomaterials are among the coarsest and softest of materials classes while having the most complex, emergent properties. Neutron scattering studies of biomaterials, especially using cold neutron techniques, are essential to master the scientific principles by which biomaterials exhibit self-assembly, self-limited growth, healing, and adaptive, emergent properties.*

## The Promise of NxGens Technology

Neutron scattering research began in the late 1940s as research reactors with considerable neutron flux were built for nuclear energy research. The first neutron source built specifically for neutron beam applications came on-line in 1958 at Chalk River, Canada. Over the past few decades, neutron scattering has emerged as the major exploratory tool for understanding condensed matter. Notably, five percent of condensed-matter publications in *Physical Review Letters* report neutron scattering results. Currently, neutron scattering is employed across the physical, chemical, engineering and life sciences.

Although many research reactors have been built for neutron scattering, over the past fifty years the thermalized neutron flux of the Chalk River reactor has been surpassed only by a factor of four. The thirty-year-old 58 MW neutron research reactor at the Institut Laue-Langevin (ILL) in Grenoble, France remains the most powerful neutron scattering facility in the world. The Advanced Neutron Source proposal (1990) at ORNL showed that neutron beam reactors of much higher brilliance than ILL cannot be built for reasonable cost. The main obstacle is heat production, which at ILL is 1.5 MW per liter of core volume (190 MeV energy released for each fast neutron produced).

The demonstration of neutron production from proton beams by spallation in the 1970s offered new hope for a source more intense than fission reactors. Heat deposition of only 25 – 30 MeV per fast neutron makes spallation



**Plutonium (5% Al alloy) exhibits at low temperature a needle-like martensitic α' phase whose structure and cause are under study. (Migliori, Albert, MST-NHMFL, Personal Communication, 2002.)**

[2]Challenges in Plutonium Science, *Los Alamos Science*, No. 26, Vol. 1-2, 2000.

[3]The European Spallation Source Project, Volumes I-IV, The ESS Council, Druckerei Plump OHG, 2002, Medium to Long-Term Perspectives of Neutron Based Science in Europe, ESFRI, 2003.

attractive compared to fission. More important, however, is the enhanced efficiency offered by the pulsed nature of the beam. Using time-of-flight (TOF) techniques, pulsed neutrons arrive at the sample and can be energy sorted and counted individually. In contrast, energy discrimination at steady-state sources requires filtering out an overwhelming fraction of the neutron spectrum.

Today's brightest-peak-flux neutron source, the Lujan Center at LANSCE, has achieved two to three times the flux of the ILL reactor at the pulse peak, while the time-average flux remains one to two percent of ILL in the most relevant range of neutron energies (1 – 100 meV). The next generation Spallation Neutron Source (SNS) at ORNL will attain twenty to forty times ILL's flux at the peak of the pulse and twenty to forty percent its time-average flux.

The *effective* intensity of a pulsed neutron source, compared with steady-state, lies between its time-average flux and its peak flux and it depends on the type of neutron experiment considered. Thus, while SNS will represent a quantum leap in performance compared to ILL in some applications, it will be inferior in others. Overall, SNS will produce fewer neutrons than ILL per unit time, but in many experiments it will provide substantial gains in data rates because of the pulsed nature of the beam.

*There is great potential in building neutron sources that combine the efficiency of pulsing with enhanced time-average flux.* This goal will be achieved using NxGens long pulse spallation source (LPSS) technology, conceived and recently demonstrated for the first time at LANSCE. The long pulse technique circumvents the limitations of the short pulse spallation source (SPSS) approach, which will be pushed close to its technical limit at SNS. The NxGens is actually complementary to SPSS. The SPSS performs best for warm neutrons while the NxGens would excel in cold (long wavelength) neutron research.

Short pulse spallation sources are limited by the proton beam energy delivered in a single proton pulse. The limit is imposed by both accelerator technology (space-charge limits in storage rings) and target degradation. In SNS and similar SPSS designs, the shock wave resulting from the deposition of tens of kilojoules within the 1 – 2 μs proton pulse poses a tremendous challenge for the target design. The 23 kJ/pulse-design goal of SNS is not far from the absolute technological limit, which is now estimated to lie in the 50 – 100 kJ range. For this reason, high-time-average flux at short pulse sources requires a high pulse repetition rate (such as 60 Hz at SNS). High repetition rates, however, limit the ability to energy-select the neutrons using time-of-flight. For an average source-to-sample distance of 25 m at 60 Hz, SPSS works well for neutron wavelengths shorter than about 3 Å. For long wavelength neutrons (4 – 20 Å) required for soft-matter and nanoscience, the frequency needs to be 10 – 20 Hz for high-efficiency.

In linear accelerators, long, energetic proton pulses (1 – 2 ms, 100 – 500 kJ/pulse) can be produced far from the space-charge limit. Moreover, long pulses avoid the target material problems since energy deposition is spread over three decades in time longer than short pulses. Such pulses still afford velocity definition for long-wavelength neutrons with flight times between source and sample in the 100 ms range. These considerations show that LPSS technology can provide more than an order-of-magnitude higher brilliance than the SPSS approach. LPSS can also surpass continuous reactor sources in terms of time-average flux and provide superior performance in all applications of neutron beam research. The trends deduced are confirmed in recently published studies by the ESS consortium.[4] The NxGens concept was tested at LANSCE in 2003 by neutron reflectivity. This study confirmed the ESS predictions regarding gains in instrument performance.

*NxGens technology will provide more than an order-of-magnitude higher brilliance than the SPSS approach, surpass continuous reactor sources in terms of time-average flux, and provide superior performance in all applications of neutron beam research.*

## Materials Science and Biosciences

A number of National Academy of Sciences' studies[5] document the materials research landscape and predict directions for the future scientific agenda. Starting with the Cohen Report in 1975, "Materials and Man's Needs,"[6] the emergence of soft-matter as a discipline is foretold. Encouraged by the National Nanotechnology Initiative (2000) and remarkable progress in molecular biology over the last five years, soft-matter research now dominates the hiring in physical sciences at research

[4] *ibid.*

[5a] Opportunities in High Magnetic Field Science: Letter Report; Committee on Opportunities in High Magnetic Field Science, National Research Council, The National Academies Press, 2004.

[5b] National Laboratories and Universities: Building New Ways to Work Together—Report of a Workshop; Committee on National Laboratories and Universities,

[5c] National Research Council, The National Academies Press, 2005.

[6] Materials and Man's Needs, *Supplementary Report of the Committee on the Survey of Materials Science and Engineering, Vol. II, The Needs, Priorities, and Opportunities for Materials Research,* National Academy of Sciences, Washington, D.C., 1975.

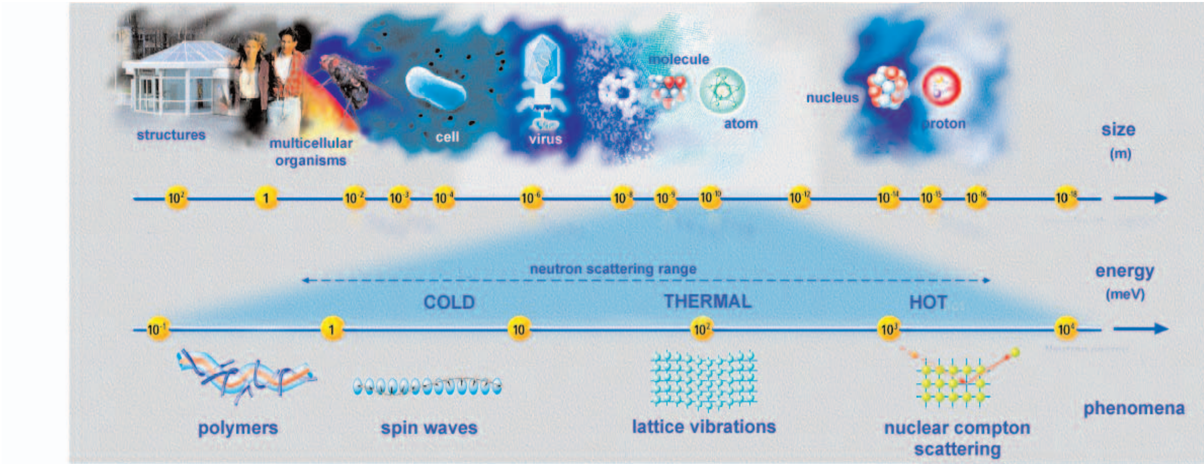



**Figure 3.** A cold neutron spectrum (depicted on the lower axis) is best for scattering from polymers, large molecules, biological systems, and other soft-materials. LANSCE leads in cold neutron peak flux and instrumentation. Enhancements through long pulse technology are needed to answer 21st Century questions.[9]

universities across the world.[7] The exceptional attributes of biological materials inspire radically new approaches to materials-limited technology. Bio-inspired ideas like self-healing, self-limiting growth, and directed assembly, once the domain of science fiction, are now the target of both venture capital and government funding. The national initiative in nanoscience and nanotechnology, for example, is directed largely at the interface between materials science and biology (see References, p. 44).

The evolution of national security priorities at LANL tracks the emergence of soft-matter as an important discipline. The traditional focus on metallurgy and condensed-matter physics has shifted toward the chem-bio-radiological threats of the terrorist era. These new priorities underlie the growth of soft-matter research, including biosciences, at LANL.

*The evolution of national security priorities at LANL tracks the emergence of soft-matter as an important discipline. The traditional focus on metallurgy and condensed-matter physics has shifted toward the chem-bio-radiological threats of the terrorist era. These new priorities underlie the growth of soft-matter research, including biosciences, at LANL.*

## Nanotechnology

Nanotechnology is another significant area of materials research enjoying worldwide expansion (Figure 3). The corresponding field of nanomaterials refers to matter intentionally organized on nanometer length scales; the feature that distinguishes nanomaterials from molecular materials where properties are determined by molecular bonding. Nanomaterials share many characteristics discussed above regarding soft materials; the essential structural features occur on supramolecular scales and the corresponding dynamics are found at lower energy. The preferred synthesis path for soft nanomaterials is bottom-up self-assembly, whereby specific short-range interactions are engineered into complex precursor macromolecules. These short-range forces induce long-range order by cooperative physical interactions. Remarkable control is demonstrated by practitioners, such as S.I. Stupp of Northwestern University.[8]

The importance of nanoscale morphology extends to hard materials as well. New processing methods produce materials textured on the nanometer scale, leading to improved mechanical properties. Equal-channel angular processing (ECAP), for example, is a method to enhance the toughness of metals by subjecting them to repetitive plastic deformation. Modern metallurgy seeks to understand the enhanced toughness in terms of the texture imposed by the deformation protocol. Neutron scattering quantifies the texture distribution.

## Materials Defects

Large-scale defects in hard materials arise due to aging in radiogenic environments and oxidation processes. Helium bubble formation in reactor vessels and neutron generators is a key issue in defense, commercial power, and threat detection technologies. Defects are analyzed using small-angle neutron scattering—a technique that will benefit greatly from NxGens.

[7]Science and Engineering Indicators 2004, volume 1, NSB 04-1, volume 2, NSB 04-1A, National Science Board, National Science Foundation, 2004.
[8]Self-assembly of Organic Nano-objects into Functional Materials, S. Stupp, et. al., *MRS Bulletin*; vol. 25, no. 4, pp. 42-48, April 2000.
[9]Adapted from the European Spallation Source Project, Volumes I-IV, The ESS Council, Druckerei Plump OHG, 2002, Medium to Long-Term Perspectives of Neutron Based Science in Europe, ESFRI, 2003.

## New Synthetic Materials

New materials synthesis seldom involves new chemical substances. Rather, known components are organized on mesoscopic length scales to achieve properties unavailable in materials organized on short scales. Materials synthesized by ECAP are one example, block co-polymers are another example. Co-polymers display properties not found in the polymers that make up their constituent blocks. The new properties arise from large-scale domains that spontaneously appear during processing, such as thin-film formation. Different domain patterns are observed depending on the chain architecture of the constituent polymer blocks. Self-assembly is an extension of this concept wherein highly specific large-scale entities (fibers, sheets, etc.) are teased into existence by short-range molecular forces. Nature uses protein chemistry to accomplish the same task in biology. These sophisticated approaches to materials development hold great promise for new materials synthesis.

Neutron scattering is a common method for structural characterization of new materials. As the complexity of materials increases, the need for neutron research also increases. The variability of neutron contrast among nuclei, particularly regarding hydrogen and deuterium, assures that neutron scattering remains the technique of choice for resolving the structure and dynamics of complex materials.

*Neutron scattering is a common method for structural characterization of new materials. As the complexity of materials increases the need for neutron research also increases. The variability of neutron contrast among nuclei, particularly regarding hydrogen and deuterium, assures that neutron scattering remains the technique of choice for resolving the structure and dynamics of complex materials.*

## National Energy Security: Hydrogen Storage, Nuclear Reactor Materials

According to national studies over the last thirty years, the properties of 21st Century materials must exceed those of today's materials by large margins. The mid-century end-of-oil challenge, for example, will elicit new hydrogen-storage materials, more efficient solar cells, better nuclear fuels and improved reactor materials.

Energy security is closely tied to materials research. From solar cells to fuel cells, breakthroughs in energy security await advances in materials. Many energy technologies involve morphologically complex materials for which neutron scattering is often the only tool capable of resolving the structure.

The DOE Office of Science supports fundamental research focused in materials science. The Office of Science also supports the nation's research infrastructure through construction and maintenance of major research facilities. With the demise of reactor-based sources, the nation's available neutron beam time has dropped drastically just as the demand for neutrons has accelerated in response to initiatives in nanoscience and bioscience. The proposed NxGens is a Generation-III source that advances neutron capability and would provide critically needed beam time to the scientific community.

*Energy security is closely tied to materials research. From solar cells to fuel cells, breakthroughs in energy security await advances in materials. Many energy technologies involve morphologically complex materials for which neutron scattering is often the only tool capable of resolving the structure.*

## Nuclear Weapons Stockpile Stewardship

The nuclear weapons stockpile requires reliable prediction of aging to maintain deterrence without nuclear testing. Numerous challenges exist with current weapons materials, particularly in extreme temperature and pressure environments. The high-peak flux and resulting high data rates of NxGens will enable real-time experiments in realistic environments by neutron scattering.

While many weapon components are fabricated from hard materials, such as ceramics and metal alloys, others are soft. Plutonium is a mechanically and electronically soft metal, with an anomalously low melting temperature, slow lattice modes that are important to performance and aging, and highly correlated electrons that drive its complex behavior. Foams, pads, high-explosives, and epoxies are also examples of soft-materials in weapons systems—all age ungracefully and exhibit unexpected behavior at interfaces. Given the importance of soft materials, long-wavelength cold neutrons are now the spectrum of choice for the national security mission.

*Cold neutrons are now the spectrum of choice for the national security mission.*

Materials used in high-consequence applications are often complex in order to optimize their performance. Here complex means not just complicated, as in a fine Swiss watch, but also unpredictable, leading to emergent or counterintuitive behavior. Plutonium, for example, is a seemingly simple array of atoms, yet its properties are exceedingly complex in ways that influence weapons' performance; the anomalous thermal expansion of plutonium is an important emergent behavior. The behaviors of uranium-niobium alloys and advanced high-explosives provide other examples.

Many weapons materials are engineered to achieve unique functionality. The challenge of stockpile stewardship is to predict these materials' properties, and other emergent behaviors, especially as they influence aging. Slow, spatially coarse processes like aging have microscopic origins suitable for study by neutron scattering. Long-wavelength neutrons are particularly attractive to probe these issues.

## Materials Challenges Regarding Nuclear Weapons Stockpile Stewardship

1) ***Plutonium Aging.*** To answer the question—what is the impact of aging plutonium on the nuclear deterrent—requires complementary probes including neutrons. While synchrotron radiation allows research at higher pressures than currently achievable with Generation-II neutron sources, the limited size of x-ray diamond-anvil samples compromises analysis of coarse morphological changes such as He-bubble formation, and typically measures properties only of the metal matrix, not the collective properties of the metal-gas composite. Cold neutron scattering is needed to address large-scale issues to complement synchrotron x-ray scattering.

2) ***Plutonium EOS and DOS.*** The existence of magnetism in Pu is predicted, yet unambiguous confirmation is lacking. Owing to strong magnetic interactions, neutron scattering is well suited to solve this mystery, which could effect understanding of plutonium's electronic density-of-states (DOS), equation-of-state, corrosion properties, and thermodynamics.

3) ***Nucleation and Growth.*** A key fundamental issue in all materials science is the nucleation of crystalline material from a melt. Recent findings show that critical nuclei may have different lattice structure from that of the bulk crystal in materials such as nickel and water. This challenging phenomenon awaits Generation-III neutron scattering for solution, possibly by single-pulse diffraction.

4) ***High-explosive (HE) Science.*** As with plutonium, understanding the materials physics of high-explosive, for example dynamic instabilities, aging, and safety, is critical to predicting weapons performance, storage, repair, and production. The NxGens provides the cold neutron spectrum necessary for a comprehensive study of HE.

5) ***Nanophase Materials.*** New processing methods produce materials textured on the nanometer scale, which can dramatically improve mechanical properties. Nanometer-scale defects can also dramatically degrade materials properties. Weapon's components suffer radiation effects, hydration and oxidation. The structure and aging of metal tritides also involves nanometer length scales. Recent experiments at the Lujan Center by Sandia National Laboratories researchers exploited the ability of neutrons to locate hydrogen to understand radiolytic generation and release of helium in erbium tritide films for neutron tubes. Detailed studies of these materials will lead to improved performance and reliable lifetime prediction of neutron tubes. The sizes of the structures of interest in these materials are best studied with cold neutrons. A NxGens source would outperform any other type of source in obtaining the required data.

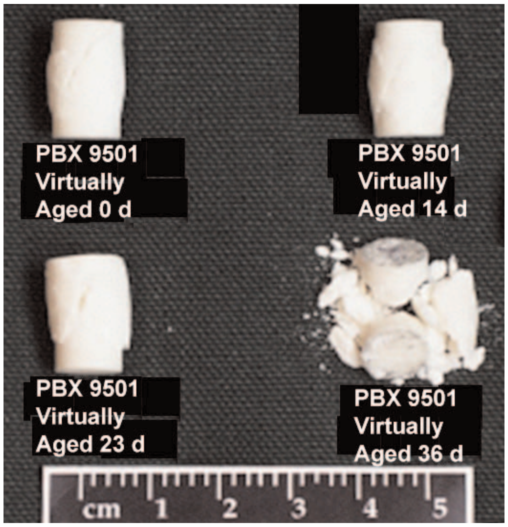
6) ***Reactive Metal Degradation.*** Many alkali metals and metal compounds, including hydrides, react rapidly with atmospheric gases, particularly water and carbon dioxide, to form corrosion layers. In virtually all uses these interactions severely limit the shelf life of alkali metal compounds. New strategies to solve these problems must be thoroughly understood through advanced tools—such as neutron scattering. For example, the rate of reaction of these metals can be reduced by the generation of passivated layers; neutron reflectivity is an ideal probe to follow such kinetics.

7) ***Polymer Aging.*** Aging of polymer components in the enduring stockpile highlights the need for a deeper understanding of polymeric materials to provide predictive capability in safety, surety, and lifetime extension. There is a lack of fundamental information on the structure and dynamics of stockpile polymers. The NxGens will provide unequalled facilities for experiments over length and time scales applicable to theoretical efforts. The data obtained will be at the core of the development of predictive capabilities.

## Homeland Security

Emerging threats fueled by terrorism demand significant materials advances. Materials will play a key role in technologies required to meet the threats of the post-cold war world. Sensors and miniaturized devices, for example, are widely recognized as technologies that require innovative new materials. Emerging threats also drive LANL's bioscience effort, which seeks not only to neutralize biological threats, but also to exploit bio-mimetic concepts to create new classes of synthetic materials. The enhanced capability of NxGens regarding large-scale structures and low-energy excitations supports these efforts.

Advances in materials science are required to meet national security and defense missions. High-performance structures for aircraft, submarines, lightweight armor, and space vehicles require new composite materials. Research in this area is focused on nanocomposites, such as polymers reinforced with carbon nanotubes. Because of the length scales involved, nanocomposites are best assessed by cold neutron methods.




**Insensitive high-explosive PBX 9501 exhibits degradation upon artificial aging. For such reasons PBX 9501 is being replaced by PBX 9502 and other formulations in the stockpile. By neutron scattering studies, the key to aging is being studied.**

Solving the structure-property puzzle for 21st Century materials requires characterization that keeps pace with advances in synthesis. For sixty years, neutron scattering has been an indispensable technique for materials characterization. In the budding nano-bio-soft-materials world, neutron sources optimized for the study of supramolecular structures and their collective motions are required. The NxGens technology matches this requirement by exploiting the production of long-wavelength, low-energy neutrons. With few exceptions, instruments needed to study soft materials will enjoy large performance gains with NxGens relative to short pulse sources—precisely what the U.S. needs.

## ENHANCEMENTS THAT ACHIEVE FULL CAPABILITY AT 800 MeV

### Lujan Center

The Lujan Center is the premier U.S. spallation neutron source. It will remain so until 2009, when the SNS is expected to surpass the Lujan Center's brightness. The strategy behind enhancing the Lujan Center is this: it ensures that LANSCE will grow in partnership with the SNS, and other megawatt-powered neutron-scattering centers, and guarantees the nation achieves maximum productivity across the broad spectrum of critical scientific endeavors dependent upon neutron scattering technology.

The Lujan Center's maximum productivity will be achieved with fourteen fully instrumented, updated flight paths, which together will accommodate 750 user-visits per year.

The strategy to achieve maximum productivity includes:

1) *Developing Flight Path 8 with the Los Alamos Pressure-Temperature Research Online Neutronmeter (LAPTRON) high-pressure instrument.* The need for high-pressure materials research for weapons, geophysics, and condensed matter establishes a need for continually upgraded capabilities. LAPTRON is an instrument design concept that would combine neutron diffraction at high temperatures and pressures with several *in situ* techniques, such as sample radiography (to establish sample volume and density), pulse-echo ultrasound (to measure elastic constants), calorimetry, and rheometry. This suite of measurements comprises the metrics-set necessary for analyzing the most challenging problems in materials physics under extreme conditions.

2) *Developing Flight Path 11b with a new inelastic scattering instrument.* New inelastic scattering instrumentation has been the top user-demand for a decade at the Lujan Center, led by the condensed-matter and chemical-physics communities. Although the DOE's Office of Basic Energy Sciences funded a backscattering, inverse-geometry instrument (SABER) in 2000, that instrument project was moved to the SNS, so the Lujan Center's user demand remains only partially fulfilled by the refurbishment, in 2003, of its High Resolution Chopper Spectrometer (Pharos). Flight Path 11b, on a cold moderator with a guide, is an ideal location for an instrument optimized for the dynamics of hydrogen. The understanding of hydrogen manufacturing, and storage fundamentals, are important for future energy applications. The design and mission for a new inelastic scattering instrument would be fully vetted with the user community.

3) *Completing Flight Path 13 with the IN500 inelastic scattering instrument.* As a Los Alamos Laboratory Directed Research and Development-funded feasibility test, IN500 has established several innovations for low-energy inelastic scattering and will undergo a final test in late FY05. Along with partially decoupled hydrogen moderators (a Lujan Center scientific innovation now common at all new spallation neutron facilities) and ballistic guide technology, the IN500 project's final test will involve an "eye-of-the-needle" chopper concept that improves electronic counting time utilization. The IN500 will illuminate slow dynamic processes in matter such as polymers, glasses, soft metals, and solutions.

4) *Fully refurbishing old instruments to competitive standards and revising new instruments to remain state-of-the-art.* The Lujan Center's Surface Profile Analysis Reflectometer (SPEAR) and

the Low-Q Diffractometer (LQD) are two older instruments that need upgrading so as to maintain their internationally competitive status. The High-Intensity Powder Diffractometer (HIPD), Filter Difference Spectrometer (FDS), and Single-Crystal Diffractometer (SCD) instruments will better benefit national research efforts by their refurbishments—and possibly complete redesigns. Examples of upgrades are adding neutron guides to Pharos and the Neutron Powder Diffractometer (NPDF) to multiply flux on-sample, modifying SCD's hutch to accommodate magnets and cryostats, and adding optics to SPEAR to change incident angles on liquid samples. The schedule for instrument refurbishment suggests that $2M per year be invested in one or two instruments; thus within seven years all instruments will be upgraded.

5) *Investing in experimental infrastructure for sample environments.* Today the Lujan Center has rudimentary cryogenic environments for materials physics, but no environments capable of 15 mK—a regime critical for condensed-matter physics where a dilution refrigerator or equivalent is needed. Compact, modest-field magnets under ten tesla, with both vertical and horizontal fields, are needed for complex materials studies, such as multiferroics. High-electric field environments are desirable to study ferroelectics in weapons applications. A recently commissioned stroboscopic rheometer on LQD demonstrates the value of stroboscopic environments that sync with the beam. Periodic mechanical stress, shock waves, and pressure jumps will nucleate new science. In many Lujan Center beam lines *in situ* laser scattering and excitation, pulse-echo ultrasound, and calorimetry could be made available in answer to the user community trend toward simultaneous, *in situ* experiments.

6) *Building a chemical-biological sample preparation laboratory.* Although the Chem-Bio Lab facilities at the Lujan Center serve users well for most research-level chemistry and biology needs, for neutron scattering experiments, the updating of the Chem-Bio Lab is long overdue. A replacement building (or new wing to the Lujan Center) will have expanded capacity for chemical hoods, a radiochemistry lab, a protein expression lab for perdeuteration of samples, a film deposition lab, a light scattering lab, optical and scanning probe microscopy lab, and a clean room for fabricating nanoscience samples.

7) *Building a research center including offices, a guesthouse, conference facilities, and other user amenities.* LANSCE enhancements envision a User Center sited on the edge of a canyon south of the Lujan Center. This building, with its spectacular views, would be the nexus of activity for users and employees of LANSCE. A guesthouse, long requested by users, would have sleeping rooms with full data access to accommodate late-night experimenters and conference attendees. Modern offices will increase visitor productivity and provide user check-in and training facilities. A cafeteria or restaurant and a coffee shop would complement the guesthouse. The research, relaxation, and intellectual center of LANSCE, the User Center will feature advanced conference facilities for hosting workshops and colloquia.[10]

8) *Building a neutron computation center with visualization facilities.* Because neutron time-of-flight data and materials simulations create some of the most challenging of computational problems, specialized tools are needed to reap the greatest benefit from neutron experiments. A computations center with state-of-the-art visualization capabilities would facilitate user experiment analysis and publication. This Computations Center, which could be incorporated into the User Center, would have high-speed connectivity to the major computing resources at the Laboratory.

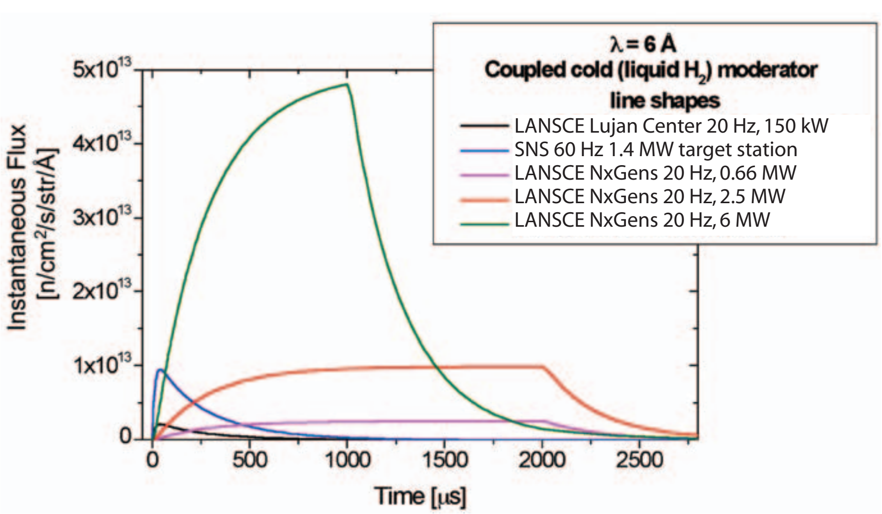



**Figure 4.** Cold neutron line shapes for various NxGens spallation source options at LANSCE compared with two SPSS sources: the Lujan Center (as of today) and SNS (in construction). The integrated flux of the LPSS pulses is fully used in applications requiring moderate-wavelength resolution, such as small-angle scattering. In applications requiring short-wavelength resolution (e.g. medium- and high-resolution diffraction), pulse-shaping choppers will be used to produce pulses with variable lengths, including shorter ones than those available at SPSS. The 6 MW calculations represent the ultimate NxGens potential.

[10] Area Development Plan: LANSCE Planning Area, Lisowski, P. W., Los Alamos National Laboratory, LA-UR-03-1771, 2004.

## NxGens

The NxGens is a cost-effective approach to complement SNS capability in the near term with a single prototype flight path, and if fully developed will substantially exceed SNS performance. *(Appendix C: Comparative Analysis of Present and Future Neutron Scattering Facilities)* The NxGens assures U.S. leadership in Generation-III neutron sources—offering unprecedented research opportunities, and drawing to LANL the brightest and best researchers.

NxGens' long pulse spallation technology has been fully vetted by the European Spallation Source project team. The results of the $40M ESS study are in the public domain.[3]

*NxGens promises a greater than one order-of-magnitude higher proton beam energy per pulse over SPSS, and a pulse structure better suited to cold-neutron techniques.*

The upgraded power capability of the LANSCE-LINAC at 800 MeV enables a prototype NxGens at 670 kW with a 20 Hz repetition rate, and 2 ms pulses. Initially a single NxGens prototype beam line will be available, built for simultaneous operation with the Materials Test Station (MTS). Instruments can be added in an incremental manner at minimal cost. After completion of the MTS mission (about 2012) the MTS facility will be converted into an optimized NxGens target station by replacing the target-moderator-reflector assembly. This process is analogous to the periodic replacement of the same assembly at current spallation sources, including Lujan Center (estimated cost $3M per target change). The MTS bulk shielding is adequate for a multi-megawatt NxGens target station without essential modification.

The prototype NxGens will perform in short-wavelength-resolution applications (e.g. diffraction and strain analysis) at about the same level as the current Lujan Center and in long-wavelength-resolution applications, at about the same level as the full-power SNS (Figure 4). Such applications include small-angle neutron scattering (SANS), reflectometry, protein crystallography, neutron spin-echo (NSE) spectroscopy and low or variable resolution time-of-flight spectroscopy.

## BEYOND 800 MeV: ENERGY AND POWER UPGRADES

LANSCE enhancement to energy and power can provide 2.5 MW at 20 Hz in 2 ms pulses to the NxGens target station. The NxGens target station will be upgraded by changing the target-moderator-reflector assembly (estimated cost $5M). The bulk shielding will not require substantial modification. The existing NxGens instruments will not need modification. At 2.5 MW the NxGens performance will substantially exceed that of SNS in cold neutron scattering and will be comparable to SNS in all other neutron scattering applications, with the exception of eV spectroscopy.

*Emerging threats fuelled by terrorism demand significant materials advances. Materials will play a key role in technologies required to meet the threats of the post-cold war world.*

*High-performance structures for aircraft, submarines, light-weight armor, and space vehicles require new composite materials. Research in this area is focused on nanocomposites, such as polymers reinforced with carbon nanotubes. Because of the length scales involved, nanocomposites are best assessed by cold neutron methods.*

Potentially all neutron scattering activity could move from the Lujan Center to the NxGens, opening the way for the construction of ten additional, state-of-the-art instruments. This migration will allow remodeling of the Lujan target–moderator assembly to provide enhanced neutron flux for fast neutron research (such as the current Detector for Advanced Neutron Capture Experiments—DANCE—science program at the Lujan Center).

The higher power Lujan target station will create a unique, high-power, fast-neutron facility for fundamental and applied nuclear physics research.

*The NxGens Generation-III long pulse neutron source would overcome intrinsic limitations of second-generation short-pulse sources and will be well suited to 21st Century materials research for academic and national security.*

## SUMMARY

Meeting national defense and national security challenges depends upon evolutionary, and revolutionary, research in soft materials, biomaterials and nanomaterials, the properties of which depend on large-scale morphological features and low-energy excitations. A Generation-III long pulse spallation source (NxGens) generating unprecedented cold-neutron flux is optimal for this research. In addition, the high-energy per pulse allows study of dynamic, time- and space-sensitive phenomena approaching microsecond time-resolution. The NxGens will open new frontiers of structural biology and dynamic self-organization of materials. Enhancements to LANSCE at 800 MeV will provide substantial improvement to

## NEUTRON SCATTERING FOR MATERIALS SCIENCE AND BIOSCIENCE

### Lujan Center

| Requirements | LANSCE Enhanced @ 800 MeV |
|---|---|
| | |
| Operational reliability of >85% for 180 days per calendar year.<br><br>Maximize cold neutron production for the study of nanophase materials, large soft-matter structures and protein crystals. | 150 kW enhanced beam power on target:<br><br>@ 20 Hz, achieves 38% of SNS cold neutron flux<br><br>@ >85% reliability for 20 years meets mission requirements.<br><br>Other Facility enhancements include:<br><br>· Developing Flight Path 8 with the LAPTRON high-pressure instrument.<br><br>· Developing Flight Path 11b with a new inelastic scattering instrument.<br><br>· Completing the Flight Path 13 IN500 inelastic instrument.<br><br>· Fully refurbishing old instruments to state-of-the-art standards.<br><br>· Investing in experimental infrastructure for sample environments.<br><br>· Building a sample preparation laboratory.<br><br>· Building a research center including offices, guest house, conference facilities, and other facility improvements.<br><br>· Building a neutron computation center with visualization facilities. |

### NxGens

| Requirements | LANSCE Enhanced @ 800 MeV | LANSCE Enhancements Beyond 800 MeV |
|---|---|---|
| | | |
| Demonstrate Generation-III cold neutron scattering technology. | Single LPSS prototype beamline.<br><br>Single flight path NxGens prototype @ 670 kW.<br><br>Enables new areas of scientific exploration in materials and bio-assembly, transient neutron diffraction, and crystallography of small protein crystals.<br><br>Up to ten beamlines available at LPSS prototype at 800 MeV with 670 kW for best-in-class cold neutron instruments, matching SNS performance. | 3 GeV @ 2.5 MW achieves full NxGens capability as a Generation-III neutron scattering facility. |

the Lujan Center, and the world's first prototype NxGens facility with best-in-class capabilities in cold neutron research. This investment would substantially increase the neutron resources available to user communities nationally and internationally.

Further LANSCE enhancement in energy will enable an optimized NxGen target station offering revolutionary capabilities (performance enhancements increased by a factor of five) for soft-matter and biomaterials research. These enhancements will give the nation both new scattering instrumentation and greatly increased available beam time—critical for new research. The NxGens will be a major national asset useful across the energy and defense missions of DOE. A thorough discussion of LANSCE enhancements is provided in *Appendix G: LANSCE Accelerator Improvement and Enhancement Options*.

The ultimate potential of LANSCE must be stressed. At 3 GeV, the LANSCE LINAC will operate at a peak current of 21 mA, and a power of 2.5 MW at 20 Hz. The NxGens will be the nation's first Generation-III spallation neutron source with capabilities well beyond SNS. *(Appendix C: Comparative Analysis of Present and Future Neutron Scattering Facilities, Table 1)*

## REFERENCES

Advancing Materials Research; Peter A. Psaras and H. Dale Langford, editors, Solid State Sciences Committee, National Research Council, The National Academies Press, 1987.

Condensed-Matter and Materials Physics: Basic Research for Tomorrow's Technology; Committee on Condensed-Matter and Materials Physics, National Research Council, The National Academies Press, 1999.

Energy and Transportation: Challenges for the Chemical Sciences in the 21st Century; Organizing Committee for the Workshop on Energy and Transportation, Committee on Challenges for the Chemical Sciences in the 21st Century, National Research Council, The National Academies Press, 2003.

The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs; Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council, The National Academies Press, 2004.

Materials in the New Millennium: Responding to Society's Needs; Proceedings of the 2000 National Materials Advisory Board Forum, National Research Council, The National Academies Press, 2001.

Materials Research to Meet 21st Century Defense Needs; Committee on Materials Research for Defense After Next, National Research Council, The National Academies Press, 2003.

Meeting the Energy Needs of Future Warriors; Board on Army Science and Technology, The National Academies Press, 2004.

Research Needs in Subsurface Science; U.S. Department of Energy's Environmental Management Science Program, National Research Council, The National Academies Press, 2000.

Summary Record of the Workshop on Polymer Materials Research: August 30-31, 1999, Woods Hole, Massachusetts; Commission on Engineering and Technical Systems, National Research Council, The National Academies Press, 2000.

## WORKSHOP ON SCIENTIFIC OPPORTUNITIES WITH A NEXT GENERATION NEUTRON SOURCE (NXGENS)

**June 7 and 8, 2005**
**Humprey's Half Moon Inn and Suites**
**San Diego, CA**

*In June of 2005, a workshop composed of key representatives from the community of spallation neutron users, hosted by LANL and the University of California, San Diego, explored the need for NxGens—the next generation spallation neutron source designed to go beyond ORNL's Spallation Neutron Source (SNS).* Workshop participants discussed the various and diverse needs for the NxGens spallation source by industry, academia, the basic and applied sciences, and national security and defense.*

*The complete report from this workshop is in press.

**Key Issues Discussed**

The participants relayed the overwhelmingly enthusiastic support by the scientific community for the development of such a source. Their discussions identified clearly the exciting research and development, over a broad scientific front, which could be addressed with more powerful neutron sources—specifically sources with an order-of-magnitude more power than SNS in the long wavelength, or "cold," neutron part of the spectrum. Such a source would enable studies at shorter length scales (in the case of thin films and surfaces), longer length scales, and at longer time scales (in the case of bulk matter) than are possible with currently conceived neutron intensities and instrumental resolutions.

NxGen's capabilities would provide critical new insights into the fundamental behavior and organization of complex materials. These include: insights into the structure, dynamics and collective behavior of nanoparticles, magnetic nanostructures, patterned films, spin-injection systems for novel electronic applications, highly correlated electron systems that have unusual superconducting, magnetic and electronic properties, and insights into materials of direct importance to national defense and security—for example, the complex nature of plutonium, whose properties are still poorly understood at a basic level, and materials for efficient hydrogen storage—such as metallic hydrides.

The possibilities for the study of "soft" materials were also discussed, and the participants found these studies particularly exciting and important. The evolution of national security priorities at LANL, and elsewhere, tracks the emergence of soft-matter as a distinct discipline. The traditional focus on metallurgy and condensed-matter physics has shifted toward the biosciences, including biomedical applications and the chemical-biological-radiological threats of the terrorist era. These new priorities underlie the growth of soft-matter research, including biosciences, at national laboratories such as LANL.

Long wavelength, cold neutrons, it was noted, are ideally suited for the study of soft, bulk materials like nano-assemblies of polymers, surfactants, fluids, porous materials, and biological systems. In soft-condensed matter, morphological features can be very large and the dynamics can be very slow. These characteristics of soft-matter drive the need for neutrons of high-intensity, long wavelengths, and in long pulses. In addition, future trends will require investigations of dilute components, as well as minority components, concentrated at topologically unique points or at interfaces. In many cases, these experiments involve polarization analysis, short-time measurements, and in situ studies.

A growing need in soft-matter studies is for simultaneous measurements involving laser spectroscopy, light scattering, ultrasound, birefringence, dichroism, electronic transport, and photophysics during pulsed neutron scattering experiments. Most of these areas are directly correlated to technological applications with a strong impact in the fields of nanotechnology and functional materials.

There is an enormous on-going effort by university, national laboratory, and industrial scientists at synchrotron sources worldwide to solve the three-dimensional structures of crystallizable proteins. Neutron crystallography, and diffuse, quasielastic and inelastic neutron scattering is expected to add invaluable complementary information—such as proton and water positions in biological macromolecules, and the dynamics of macromolecules and biomembranes at the atomic and molecular levels. For such studies to make an impact, however, the highest neutron fluxes in the long wavelength region are essential.

The increased beam intensity available in a NxGens source would make feasible *in-situ* real-time diffraction studies of slow phase transitions, strain-dependent phenomena, and biological processes, evolving over a period of seconds to minutes.

In the view of the workshop's participants, the most demanding and exciting experiments at the frontiers of science will require the capabilities of the next generation of long pulse spallation sources—NxGens. The accelerator technology for NxGens currently exists. The advent of the Materials Test Station, at the LANSCE facility at Los Alamos National Laboratory, would provide an ideal opportunity to test a prototype of the NxGens long pulse spallation neutron source.

**Participants**

Michael Agamalian, Oak Ridge National Laboratory
Shenda Baker, Harvey Mudd College
Jack Carpenter, Argonne National Laboratory
Bruce Clemens, Stanford University
Gian Felcher, Argonne National Laboratory
Mike Fitzsimmons, Los Alamos National Laboratory
Mike Fluss, Lawrence Livermore National Laboratory
Geoff Greene, Oak Ridge National Laboratory
Alan Hurd, Los Alamos National Laboratory
Bill Klein, Boston University
Paul Langan, Los Alamos National Laboratory
Chip Lesher, University of California, Davis
Paul Lisowski, Los Alamos National Laboratory
Chuck Majkrzak, National Institute of Standards and Technology
Feri Mezei, Los Alamos National Laboratory
Albert Migliori, Los Alamos National Laboratory
Ken Nagamine, University of California, Riverside
Steve Nagler, Oak Ridge National Laboratory
Atul Parikh, University of California, Davis
Roger Pynn, Los Alamos National Laboratory
Jim Rhyne, Los Alamos National Laboratory
Kurt Schoenberg, Los Alamos National Laboratory
Benno Schoenborn, Los Alamos National Laboratory
Ivan Schuller, University of San Diego
Sunil Sinha, University of California, San Diego
Mark Yeager, Scripps Research Institute

*Author:*
*Sunil Sinha, University of California, San Diego*

# Chapter 3

## Materials Testing: *An* Irradiation Capability *for the* Development *of* Fast Spectrum Systems


Mike Cappiello, *AFC-PO*
Rick Wood, *LANSCE-ABS*
Brad Bergman, *LANSCE-ABS*
Erich Schneider, *D-5*
Mike James, *D-5*
Larry Rybarcyk, *LANSCE-ABS*
Stuart Maloy, *MST-8*
Ron Selvage, *LANSCE-TMS*
John Eddleman, *LANSCE-MDE*
Eric Pitcher, *LANSCE-DO*
Keith Woloshun, *LANSCE-NS*
Dan Rusthoi, *AFC-PO*

COOLING TOWERS FOR LANSCE'S LINEAR ACCELERATOR BEAM LINE (LINAC)

# Materials Testing: An Irradiation Capability for the Development of Fast Spectrum Systems

*"The expansion of nuclear energy is recommended as a major component of our national energy policy. Key elements of this goal are the Generation-IV Advanced Fuel Cycle Initiatives."*

*— From Energy for a New Century, U.S. National Energy Policy, 2004.*


## ABSTRACT

To meet the missions of the Generation-IV and Advanced Fuel Cycle Initiative the U.S. needs a new fast neutron irradiation capability to prove the performance of new fuels and advanced materials. This new capability is possible with the use of the 800 MeV energy protons from the LANSCE accelerator, coupled with a spallation neutron production target. A Materials Test Station (MTS) will be built in the existing experiment hall and, with LANSCE's refurbishment (LANSCE-R)[1], a reliable high-power beam will be delivered. The MTS effectiveness can be enhanced with accelerator upgrades of energy and current over the next ten years to a neutron intensity level equivalent to a 100 MW fast-test reactor. The MTS irradiation capability, in concert with existing post irradiation examination capability in local hot cells, will provide necessary and timely data for the validation of materials simulation models, enhancing the science-based prediction of materials behavior. This capability will be an integral component of the fast-reactor development program as the country's premier source of high-intensity fast neutrons, and supports the schedule for the introduction of a demonstration test reactor in the 2020 time frame. In addition, the LANSCE-MTS will provide the capability to develop advanced materials needed for fusion systems, and the capability to generate unique nuclear isotopes for medical research and defense applications.


## INTRODUCTION

The development of commercial nuclear power has successfully relied on thermal neutron spectrum (mostly water-cooled) reactors over the past fifty years. Fuel utilization, proliferation, and waste issues have revitalized interest in the fuel cycle and fast-neutron-spectrum fission systems because of the efficiency in the transmutation of actinides. The higher actinides (plutonium, americum, neptunium) are the long-lived components of nuclear waste. This characteristic is what drives the long-term issues of decay, heat, and radio-toxicity. These, in turn, effect repository capacity and performance.

To address these issues and to support the National Energy Policy, the Department of Energy (DOE) initiated several programs to help revitalize nuclear power generation growth in the United States. Two important programs are the Generation-IV Advanced Reactor Program (Gen-IV) and the Advanced Fuel Cycle Initiative (AFCI). Their programmatic goals are designed to stimulate research and development related to advanced reactor concepts and fuel cycles over the next thirty years.

Part of the Gen-IV and AFCI focus is directed toward reactor and fuel cycle concepts that can reduce the spent fuel demands on geologic repositories by improving the utilization of fuels and transmutation of long-lived transuranics. These advanced concepts employ nontraditional fuels, structural materials, and coolants for which sufficient operating knowledge does not exist. To assess the fuel performance of these candidate reactor fuels, such as the minor actinide fuel concentrates, these fuels must be irradiated under actual or prototypical fast-reactor flux conditions and operating environments. Structural materials for advanced reactors will also require a sophisticated irradiation capability with special coolant environments for corrosion studies. Currently there are no fast-reactors or fast-flux test facilities in the U.S. that meet the prototypic irradiation environment required for the Gen-IV/AFCI programs.

Fast-neutron-spectrum test facilities are available overseas, and within the AFCI program tests are being planned for the PHENIX reactor in France and the JOYO reactor in Japan. After the planned shutdown of the PHENIX reactor in 2008, the JOYO and perhaps BOR60 in Russia will be the only fast spectrum facilities available worldwide in which to perform the necessary tests. Testing overseas is expensive and time consuming. For example, to perform an irradiation of just a handful of experimental test pins, the cost premium for the U.S. to use the PHENIX reactor is approximately $5M, and the added time necessary to retrieve data is approximately two years. An advanced facility is needed in the U.S. to provide a quicker turnaround of experimental results, and to provide a cost effective irradiation service.

*An advanced facility is needed to provide the U.S. a quicker turnaround of experimental results, and to provide a cost effective irradiation service.*

With respect to fusion energy, there are no intense sources of 14 MeV neutrons sufficient for materials irradiations.

To meet current and future U.S. energy needs, LANSCE must produce neutrons of sufficient intensity to research and optimize the next generation of materials and fuels necessary

[1]Proposed Line Item LANSCE Refurbishment Project, Lisowski, P. W., LA-UR-04-1350, 2004.

to deploy advanced fission systems.This unique capability will be possible with the use of the 800 MeV energy protons from the LANSCE accelerator, coupled with a spallation neutron production target yielding a steady-state flux of $10^{15}/cm^2/s$. A Materials Test Station (MTS) will be built in the existing experiment hall *(Appendix D: Materials Test Station Figure 1, Area A)*. The irradiation capability can be enhanced with accelerator upgrades of energy and current over the next ten years to a neutron intensity level equivalent to a 100 MW fast-test reactor ($3 \times 10^{15}/cm^2/s$). The materials irradiation capability, in concert with the post irradiation examination capability, will provide necessary and timely data for the validation of materials simulation models, thereby enhancing our science-based prediction of materials behavior. This capability will be an integral component of the U.S.'s fast-reactor development program, creating the country's premier source of high-intensity fast neutrons. In addition to fission energy research, the MTS will make LANSCE a premier facility capable of developing the advanced materials needed for future fission and fusion systems.

Finally, the MTS will generate unique nuclear isotopes, without compromising the existing experimental capability or impacting scheduled operations. By using isotope production targets integrated with the spallation neutron source, specific isotopes of high radio isotopic purity can be produced that are not currently available. This capability will complement the existing DOE isotope production program managed by the Office of Nuclear Energy Science and Technology. By using the MTS intense neutron environment, certain radioisotopes can be produced for defense programs.

*Currently there are no intense sources of 14 MeV neutrons sufficient for fusion materials irradiations. The Materials Test Station will mimic fusion first-wall conditions and make LANSCE a premier facility for developing the advanced materials needed.*

## REQUIREMENTS

Although irradiations and isotope production were done in the past at the high-energy-beam-stop region of LANSCE, currently there is no capability for material irradiations. The Lujan Center produces an intense source of neutrons, but because of the pulse nature of the source, and the fact that neutrons are moderated for scattering experiments, makes it unsuitable for high-dose fast-spectrum irradiations. To maintain this strategic area of excellence a new materials irradiation capability is needed.

To develop advanced fission systems, and to advance the non-proliferating fuel cycle strategy, the U.S. Department of Energy's Office of Nuclear Energy Science and Technology is investing in the Advanced Fuel Cycle Initiative (AFCI) and the Generation-IV Program. The National Nuclear Security Administration's (NNSA) Office of Naval Reactors is developing fast-spectrum reactors for deep space exploration. The Department of Energy's Office of Science is focusing fusion energy research on the development of the International Thermonuclear Experimental Reactor (ITER). The materials and fuels research needs of each, which LANSCE's Material Testing Station will meet, are outlined below.

### Office of Nuclear Energy Science and Technology: AFCI and the Generation-IV Program

The AFCI is developing high-burn-up-fuel, with a significant inclusion of plutonium and higher actinides. Different fuel forms and different formulations of constituents will be used. The success of these cannot be judged until they are irradiated and tested. The actinide bearing fuels, and new advanced structural materials for cladding and core components, need proof-of-performance demonstration before they can meet the schedule for a new demonstration reactor to be built in the 2020 time frame. Both fast-spectrum reactors and accelerator driven systems are considered as possible candidates for transmuting these isotopes.

Fast-spectrum-neutron-capable fuels will provide an efficient method for the transmutation of plutonium and minor actinides. This is due to their larger fission-to-capture ratio in this spectrum. Reduction of the plutonium inventories significantly reduces the issues surrounding the proliferation of materials.

A top priority of the Generation-IV program is to develop a fast-reactor to achieve significant advances in long-term proliferation resistance and sustainability. A twenty- to twenty-five-year time frame is required for the development of the fast-reactor system, and several coolant technology options (gas, lead, sodium) are being assessed. This plan fits with the future need for a sustainable U.S. nuclear fuel cycle. It allows for about ten years of research and development of several promising candidates, followed by selection of one technology, and a demonstration of all elements of a closed fuel cycle, within a decade thereafter.

To prove the performance of AFCI and the Generation-IV program, MTS's fast-spectrum neutron environment is needed for irradiation of fuels and materials.

### Office of Naval Reactors: The Space Reactor Program

For deep space missions, as well as extended missions to the moon or Mars, nuclear energy is the clear choice. The Space

*A top priority of the Generation-IV Program is to develop a fast-reactor to achieve significant advances in long-term proliferation resistance and sustainability. For deep space missions, as well as extended missions to the moon or mars, nuclear energy is the clear choice.*

*To prove the performance of future reactors, MTS's fast-spectrum neutron environment is needed for irradiation of fuels and materials.*

Reactor Program is developing reactor technologies to provide robust and efficient energy sources for electricity and propulsion.

To increase efficiency for electricity production, and for direct thermal propulsion, very high temperatures are necessary. Fast-spectrum reactors, with both gas and liquid metal coolants, are being considered. To validate the performance of fuel and materials in these extreme conditions, MTS's versatile fast-spectrum neutron irradiation environment is needed for materials irradiation testing.

## Office of Science: The Fusion Energy Program

The Fusion Energy Program is focused on the development of electromagnetic heating and confinement of tritium-deuterium plasma. Fusion reactions in the plasma release energy in the form of 14 MeV neutrons. These neutrons interact with the first wall's structural material and the lead-lithium coolant. Because the neutrons are above the threshold energy for (n, p) and (n, alpha) reactions, gas production in the first wall's material becomes a serious lifetime issue. Production of 14 MeV neutrons in sufficient intensity is needed for materials irradiation.

This need is partially addressed with MTS's materials development program. In the absence of a mono-energetic 14 MeV source, the MTS can provide an alternate irradiation capability that simulates the gas production in a consistent ratio with other damage parameters.

The materials irradiations requirements for these different programs are summarized in Table 1.

Clearly, to prove the performance of the various systems, fuels and materials must be researched, characterized, fabricated, irradiated and examined. Previous research shows that fuels and materials behavior are functions of the burn-up, displacements per atom (dpa), and helium production. Independent of these parameters, but equally important, is the temperature at which materials are irradiated, and the neutron spectrum of irradiation. Thus, irradiation and testing in a prototypic environment is ultimately needed.

## The Materials Test Station Will Meet the Irradiation Needs

The MTS will be implemented in parallel with LANSCE-R. The MTS is designed to provide an environment for irradiating

**TABLE 1. MATERIAL IRRADIATION REQUIREMENT**

| Program/System | Neutron Intensity ($n/cm^2/s$) | Neutron Spectrum | Helium Generation (He/dpa) | Coolant(s) | Coolant Temperature |
|---|---|---|---|---|---|
| AFCI/Burner Reactor | $2 \times 10^{15}$ | Fast Neutrons (Fission) | 0.1 – 1.0 | Lead, Lead Bismuth, Sodium | 400 – 600 °C |
| AFCI/Accelerator Driven System | $2 \times 10^{15}$ | High-Energy Protons, Fast Neutrons and Scattered Protons | 0.1 – 150 | Lead, Lead Bismuth | 350 – 550 °C |
| Gen-IV/Lead Fast-Reactor | $0.7 \times 10^{15}$ | Fast Neutrons (fission) | 0.1 – 1.0 | Lead | 550 – 650 °C |
| Gen-IV/Gas cooled Fast-Reactor | $1.0 \times 10^{15}$ | Fast Neutrons (fission) | 0.1 – 1.0 | Helium | 900 – 1000 °C |
| Space Reactor | $0.2 \times 10^{15}$ | Fast Neutrons (fission) | 0.1 – 1.0 | Lithium, Helium, Heat Pipes | 1000 °C |
| Fusion Energy | $1.0 \times 10^{14}$ | 14 MeV mono-energetic | 10 | Lead Lithium | 500 °C |

materials in a versatile configuration of samples, targets and choice of coolants. A unique neutron flux-trap arrangement produces a high-intensity-fast-neutron spectrum similar to the fast-reactors being researched by the AFCI and Gen-IV programs. Experiment samples will be temperature controlled and highly instrumented. Special closed loops will be available to provide the coolant and temperature environment as needed. A combination of both the high-intensity-fast-neutron environment coupled with the ability to control temperature and coolant type will be unique in the world. This capability will allow researchers at LANSCE to advance the state-of-the-art in fuel and materials in a timely manner in preparation for deployment of a demonstration system. Fusion energy materials scientists and space reactor researchers can also make use of this unique capability.

In addition to the capability to irradiate materials, unique isotopes can be produced at the MTS for either medical research or for defense applications. Furthermore, they can be produced while running simultaneously, with minor impact on the materials irradiation mission. The neutron-rich isotopes can be created in sample tubes at the periphery of the neutron source and unique spallation induced neutron-poor isotopes can be created within the spallation target itself. These isotopes are complementary to those isotopes produced at the current LANSCE Isotope Production Facility that extracts a portion of the LANSCE beam at 100 MeV.

**TIMELINE OF MTS MAJOR MILESTONES**

| Date | Action |
|---|---|
| CD-0 | 12/2005 |
| Start Construction | 5/2006 |
| Start Commission: Begins Materials Proof of Performance | 9/2009 |
| Begin First Irradiation Campaign | 1/2010 |
| Materials Proof of Performance for AFCI and Gen-IV Programs Complete | 1/2017 |

## COST ESTIMATE

Preliminary costs estimates for the MTS show that the funding required is very reasonable considering the capability that is achieved. The estimated costs to complete the Materials Test Station are roughly summarized in Table 2. The difference between the “lower” and “higher” cost is the contingency estimate, which varies among the items. These estimates are based on assumed escalations of labor and procurement costs.

**TABLE 2. ESTIMATED COSTS TO COMPLETE THE MATERIALS TEST STATION**

| Task | Lower Cost | Higher Cost |
|---|---|---|
| Pre-Conceptual Design Activities | $2.5M | $3.0M |
| Preliminary and Final Design Activities | $5.5M | $7.0M |
| Procurement, Fabrication, Assembly, & Installation | $15.5M | $19.5M |
| Target Area Preparation | $10.0M | $16.5M |
| Safety Analysis and Operating Procedures | $1.3M | $1.5M |
| Commissioning | $1.7M | $2.5M |
| **Totals** | **$36.5M** | **$50.0M** |

NOTE: The above is based on preliminary funding assessments. Final funding determinations have not been made. Operation costs are ~$5–10M per year for operation.

## LANSCE ENHANCEMENTS MEET THE REQUIREMENTS

The LANSCE-R accelerator refurbishment project will allow delivery of a reliable high-power beam—up to 1 mA. The MTS will provide a materials and fuels irradiation capability with fast neutron intensity up to 1 x $10^{15}$ n/cm$^2$/s.

Future accelerator beam current upgrades will allow a 2 mA beam to be delivered to the MTS. This will allow an attendant doubling of the neutron intensity to 2 x $10^{15}$ n/cm$^2$/s and increase MTS effectiveness by reducing the time necessary for irradiations

Future accelerator energy upgrades to 3 GeV will increase the neutron flux intensity to 5 x $10^{15}$ n/cm$^2$/s over a larger irradiation volume. This upgrade gives the MTS a truly unique irradiation capability on par with the highest power fast-spectrum reactor. A thorough discussion of LANSCE enhancements is provided in *Appendix G: LANSCE Accelerator Improvement and Enhancement Options*.

## SUMMARY

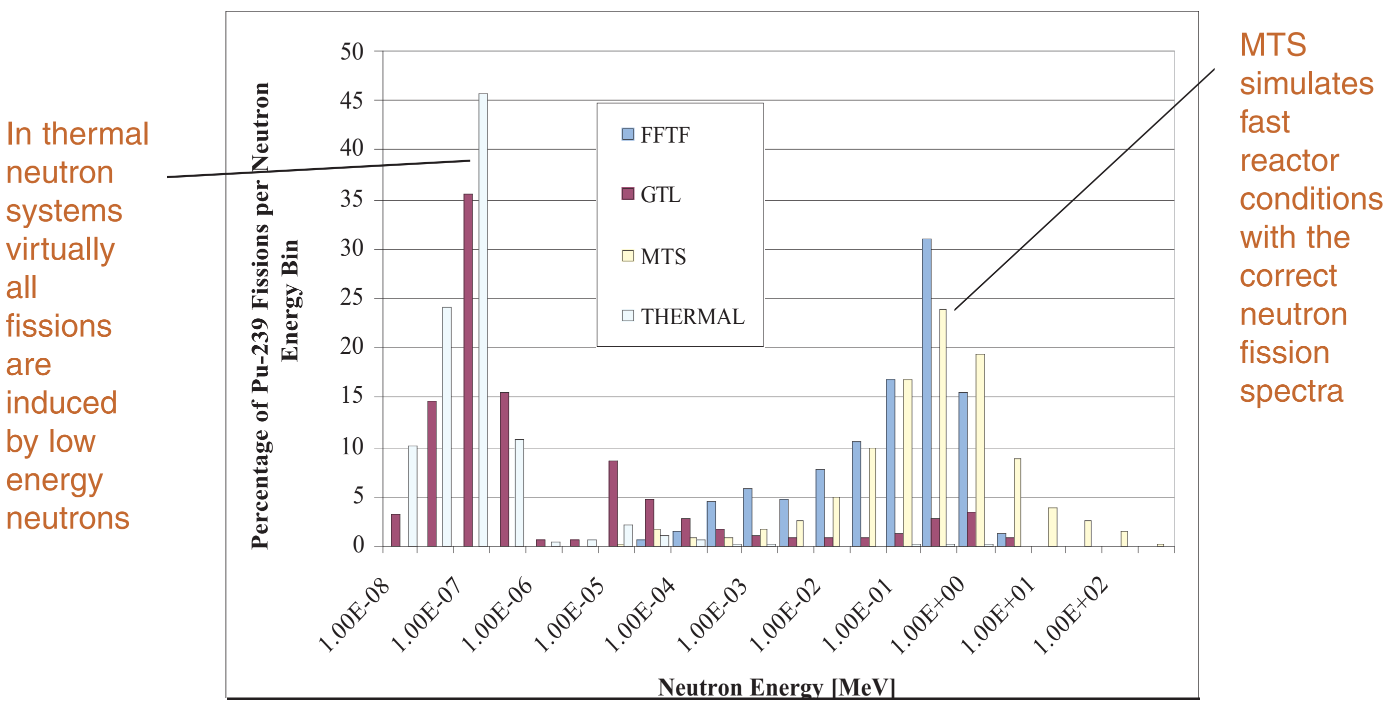
At present, the U.S. has no broad-spectrum irradiation facilities for the testing of fast-neutron-spectrum fuel cycle and reactor concepts. Testing is currently done in the U.S. in thermal neutron spectrum reactors. The LANSCE-MTS is a cost-effective and timely solution to provide fast-neutron-irradiation capability. With the ability to control sample temperature and coolant in a fast-neutron-irradiation environment, LANSCE-MTS provides a unique capability for experimenters. Building a new fast-flux test reactor of sufficient power (100 MW) to achieve the required high-intensity neutron flux would cost approximately $1 billion. The MTS can provide a similar irradiation capability (albeit over a smaller volume) for a fraction of this cost. And because of the unique features of spallation neutrons, the MTS can mimic the materials irradiation effects expected in advanced fusion systems.

Providing a new domestic fast-neutron testing capability holds the best guarantee that program objectives will be met on time and in a cost-effective manner. The other options available entail substantially higher cost and risk of delays. The broad testing requirements of AFCI and Gen-IV demand the availability of reliable and sophisticated irradiation facilities in the U.S. for fuels and materials research.

## CIVILIAN NUCLEAR SCIENCE

| Program/Science | Requirements | LANSCE Enhancements |
|---|---|---|
| | | |
| Materials Science: Materials Test Station (MTS) | MTS enables the radiological testing of materials for AFCI/Gen-IV program. 800 kW of beam power meets MTS project specifications of 1 x $10^{15}$ n/cm$^2$/s. | Raising the beam power to 1600 and 3000 kW will produce from 2 x $10^{15}$ to 5 x $10^{15}$ n/cm$^2$/s, respectively. |

### THE MTS WILL PROVIDE THE CORRECT SPECTRUM TO TEST FAST-REACTOR FUELS



## WORKSHOP ON GLOBAL NUCLEAR FUTURES AT LANSCE: NUCLEAR ENERGY AND ISOTOPE PRODUCTION

**August 22-24, 2005**
**Fairmont Hotel, Washington DC**

*To gather information and recommendations from the LANSCE user community, regarding the refurbishment and the future evolution of LANSCE, the Los Alamos National Laboratory invited key user representatives to a workshop: Global Nuclear Futures at LANSCE.* Invitees were charged with focusing on the role that accelerator science plays in addressing challenges for the national and global nuclear future—with a special interest in the science of nuclear energy and the production of isotopes.*

### NUCLEAR ENERGY

**Key Issues Discussed**
The key issues centered on the U.S. capability to test advanced reactor fuels and materials, and fusion materials, in a prototypic environment, and the need for a domestic Materials Test Station to provide this capability. The Advanced Fuel Cycle Initiative (AFCI), the Generation-IV reactor program, and the Fusion Reactor Development program need irradiation facilities to develop advanced, radiation resistant materials and high burn-up transmutation fuels. The AFCI and Generation-IV programs are developing new transmutation fuels that will allow the nearly complete burn-up of the spent fuel actinides that dominate repository heat and toxicity issues.

To meet the missions of the Generation-IV and AFCI the U.S. needs a new domestic fast neutron irradiation capability in order to demonstrate the satisfactory performance of new fuels and advanced materials. This new capability is possible with the use of medium energy protons from the LANSCE accelerator, coupled with installation of a new spallation neutron-production target, with the implementation of the Materials Test Station.

### ISOTOPE PRODUCTION AND APPLICATIONS

**Key Issues Discussed**
Nuclear medicine has been called the most successful example of technology transfer from the government to the private sector since the dawn of the atomic age. The U.S. needs new isotopes, and new technologies, that will become the lifesaving tools, and the business opportunities, of tomorrow. A five-year market trend indicates large increases in the need for isotopes for current clinical and research applications. The Isotope Production Facility (IPF) is essential to satisfy current, and future, demands for the isotopes used in nuclear medicine and research. The IPF's role in developing new research-isotopes can lead to new markets. Without LANSCE, and the IPF, many of these customer requirements will not be satisfied. The isotopes produced at LANSCE have not, or can not, be made elsewhere. With further enhancements LANSCE, together with the University of New Mexico's Center for Isotopes in Medicine, could become the center for the development of medicines that incorporate isotopes for both diagnosis and therapy.

The IPF supports important environmental science. For example, the isotope silicon-32 is produced uniquely at LANSCE. Substituting stable silicon-30 with the isotope silicon-32 plays a key role in the study of biological oceanography and climate change. The ongoing production of silicon-32 will be required for the long-term to support research studies that are looking into the role silicon-based organisms play in ocean processes, and their effect on climate processes.

The IPF can support national security R&D because of the availability of many radioisotopes not available from other sources, isotopes with nuclear weapons applications. Availability of exotic radioactive isotopes, created from tracer packages during nuclear events, can lead to improved cross section data for these isotopes, and are used to better model and understand device performance. Isotopes with homeland security implications were also briefly discussed. The IPF and the proposed Materials Test Station should collaborate in the coordination of production of isotopes, and together potentially cover much of the Chart of the Nuclides. Development of an isotope production capability, as part of the planning, design, and construction of the Materials Test Station, will represent a significant upgrade to the Laboratory's and the nation's isotope production capabilities. New isotopes in the LANSCE portfolio will lead to new applications in medicine, science, and in homeland and national security.

In addition, the IPF is crucial to the education and training of nuclear scientists.

**Key Workshop Outcomes and Recommendations Include:**
1. It is strongly recommended that LANSCE refurbishment (LANSCE-R) proceed to ensure beam reliability and availability. This is critical for physics research, isotope production and research, industrial semiconductor quality testing, and ongoing defense programs.

---

* For the complete workshop report, see Global Nuclear Futures at LANSCE: Fifth in a Series of Workshops Exploring the Future of the LANSCE Facility at Los Alamos National Laboratory, August 22-24, 2005, Fairmont Hotel, Washington DC, Christensen, D., et al., Los Alamos National Laboratory, LA-UR-05-7330, 2005.

2. It is highly recommended that the Materials Test Station be constructed. The MTS will provide the first fast neutron irradiation capability in the U.S. since the shutdown of Fast Flux Test Facility and the Experimental Breeder Reactor-II.
3. It is highly recommended that enhancements beyond LANSCE refurbishment take place to double the beam current, thereby providing a significant increase in proton flux or irradiation volume. This will further increase the functionality of the MTS, and provide testing capability similar to foreign fast reactors. A further increase in beam energy to 3 GeV will increase the flux by a factor of five, making the MTS useful for accelerated testing of fuels, materials, semiconductors, and so forth.
4. It is highly recommended that instrumentation be enhanced. Improvements in detectors, electronics, and data acquisition with the present LANSCE beams will result in large improvements in experimental capabilities and productivity both for nuclear data and for nuclear physics.
5. It is highly recommended that a 100 MeV capacity for the IPF be supported. The IPF can play a crucial role in future availability of isotopes for national security and homeland defense—isotopes otherwise available without a major burden on these core mission programs—and provide education and training of nuclear scientists for core mission programs.

**Participants**
Roy Brown, CORAR Corporation
Mark Brzezinski, University of California, Santa Barbara
Mike Cappiello, Los Alamos National Laboratory
Phillip Finck, Argonne National Laboratory
Frank Garner, Pacific Northwest National Laboratory
Jeff Norenberg, University of New Mexico
Francois Nortier, Los Alamos National Laboratory
John Pantaleo, U.S. Department of Energy
Eugene Peterson, Los Alamos National Laboratory
Eric Pitcher, Los Alamos National laboratory
Arthur Rowcliffe, Consultant
James Tulenko, University of Florida
Dave Vieira, Los Alamos National Laboratory

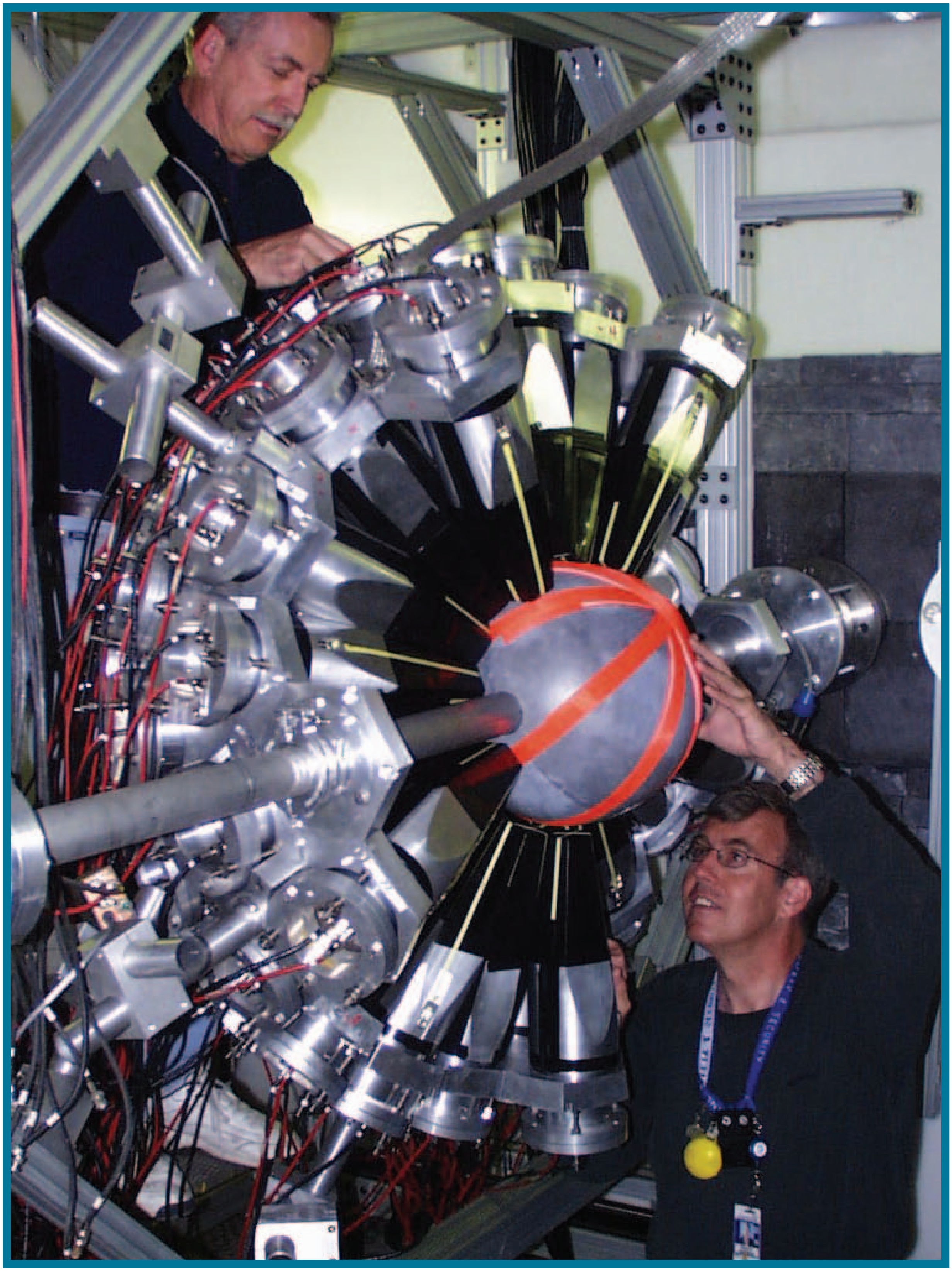
*Authors:*
*Michael W. Cappiello*
*Dana C. Christensen*
*Robert C. Haight*
*Allen Hartford, Jr.*
*Eugene J. Peterson*
*Stephen A. Wender*

# Chapter 4

## Nuclear Science *and the* Physics Certification *of* Nuclear Weapons

Steve Wender, *LANSCE-NS*
Steve Howe, *X-2*

HALF OF THE DETECTOR FOR ADVANCED NEUTRON CAPTURE EXPERIMENTS (DANCE)



# Nuclear Science and the Physics Certification of Nuclear Weapons

*"We must have ways to ensure the safety, security and reliability of the weapons stockpile. We need to understand how they work at an atomic level, understand how they age. Neutron science is key to understanding the operation of nuclear weapons..."*

*— Louis Rosen, Senior Fellow Emeritus, Los Alamos National Laboratory*


## ABSTRACT

The U.S. is facing tough challenges with the rise of terrorism and the proliferation of nuclear weapons by rogue nations. The prohibition of nuclear weapons testing accentuates the need to accurately predict the safety, security, reliability, and yield of stockpiled nuclear weapons. The nuclear science program at LANSCE provides the U.S. nuclear weapons program with data critical to meeting these missions. Upgrading the LANSCE accelerator will increase the duty factor of the beam and enable experiments beyond our present capabilities. In addition, upgrades to the instruments will increase the sensitivity of the detectors, permitting experiments not presently possible. Expanding isotope production will allow the fabrication of radioactive samples and experiments on short-lived isotopes, again not currently possible. The installation of a Materials Test Station (MTS) will provide sufficient increases in neutron intensities for new capabilities in neutron radiography for a variety of surveillance applications, and the capability to produce radioactive samples for the measurement of isotopes in the weapons radiochemical network.


## INTRODUCTION

Computational modeling of the performance of a nuclear weapon depends on accurate nuclear data over a broad neutron-energy range. For many years, researchers from LANL and Lawrence Livermore National Laboratory (LLNL) have utilized LANSCE's capabilities to measure a host of nuclear cross-sections pertinent to understanding the processes in a nuclear device.

Nuclear data are crucial to two major aspects of stockpile stewardship:

1) The ability to accurately calculate the nuclear energy production as a function of time in a nuclear detonation, and
2) The ability to benchmark calculated nuclear performance against previous above ground or underground test data.

The ability to calculate, from first principles, nuclear yield depends on accurate energy production cross-sections of weapons materials, including daughter products, and the elastic and inelastic cross-sections necessary to accurately predict neutron transport.

The broad-spectrum spallation sources, the capabilities for fabricating and handling actinide and other radioactive materials, and the associated instruments such as the Germanium Array for Neutron-Induced Excitations (GEANIE), the Detector for Advanced Neutron Capture Experiments (DANCE), Fast-Induced Neutron Gamma-ray Observer (FIGARO), and FISSION (online in 2006) provide unmatched facilities for addressing nuclear data needs of the weapons program and the defense complex, as well as nuclear energy, industry, and basic research. Upgrades to these instruments, along with increased beam intensity, enables measurements of reactions to be completed in shorter time, using smaller samples of material, and with significantly reduced uncertainties.

Comparison of calculated performance to past test data relies almost exclusively on radiochemistry. Radioactive isotopes are produced by neutron reactions on plutonium, uranium and radiochemical (radchem) tracer elements. The ratios of these isotopes after a test is the principal mechanism used to determine the yield of the tested device. Despite a continued and successful program to measure nuclear cross-sections, many of the cross-sections of meta-stable states and short-lived radioisotopes have not been measured. Improvements in the LANSCE beam structure and beam current will open an entirely new list of samples for study that are present in a nuclear device—but up to now have only been calculated theoretically.

A host of new isotopes could be generated and measured for which no experimental data exists. Measurement of the reaction cross-sections for many of these radioactive isotopes will reduce the uncertainties in estimated yields from underground tests (UGTs) and help refine the physics models in the design codes. Improvement in the LANSCE beam intensity, coupled with improved ability to create, isolate, and measure cross-sections of short-lived isotopes, will reduce the time and cost of measuring the currently planned suite of reactions to support National Nuclear Security Administration's Advanced Simulation Computing program (ASC) milestones.

In addition to the nuclear data program, there are two new additional directions for development at LANSCE with the potential to significantly contribute to the nuclear weapons program:

1) Radiation effects on electronics, and
2) Neutron radiography.

The possibility of using the neutron flux at LANSCE to test the sensitivity of electronics to weapon effects is based on an existing program at the Sandia National Laboratories (SNL). Historically, SNL utilized the Sandia Pulsed Reactor (SPR), a fast-pulsed reactor, to irradiate the electronics. The SPR is being shutdown within the next two years. By impinging the LANSCE proton storage ring beam onto a specially designed target, a sufficient flux of "fission spectrum" neutrons will be generated to perform the verification and potentially replace the SPR function.

*Improvement in the LANSCE beam intensity, coupled with improved ability to create, isolate, and measure cross-sections of short-lived isotopes, will reduce the time and cost of measuring the currently planned suite of reactions to support the ASC milestones.*

Neutron radiography has the potential of complementing other radiographic techniques (x-ray or proton) for specific stockpile applications. Neutron radiography "sees" the presence of low-Z materials such as high-explosives or plastics inside of dense materials. The neutron spectrum produced at LANSCE's Weapons Neutron Research facility (WNR) has characteristics that enable new, non-destructive methods to assess the condition of components. Development of the Materials Test Station (MTS) will produce an intense flux of high-energy neutrons enabling rapid, non-destructive scanning of assembled components from the stockpile, or for accurately measuring hydro-test components.

*A narrow pulse of fission-spectrum neutrons will be used to develop prompt diagnostics for UGTs and to train a new generation of scientists to use prompt diagnostics. Improvements in the existing detector arrays will allow significant expansion of capabilities pertinent to the weapons program.*

## NUCLEAR DATA FOR THE IMPROVED PREDICTION OF STOCKPILE PERFORMANCE

### Background

A more complete analysis of previous nuclear test data is dependent upon accurate knowledge of nuclear reaction rates. Because nuclear testing is no longer performed, the accuracy of the cross-sections is of higher importance; these data constrain and define the accuracy of weapons code predictions, and therefore impact the confidence in predictive capability. Uncertainties in the cross-sections directly impact the uncertainty of weapons code predictions of the isotopic ratios measured in past underground tests.

***Fission-Yield***

Radiochemical diagnostics play an important role in understanding nuclear detonation. One method to determine yield is to measure the amount of specific isotopes produced by the fission process. For example, neutrons impacting the fissionable material can be captured (n, $\gamma$) or produce secondary neutrons (n, 2n) to generate different isotopes of the parent nucleus. If the ratios of the probability for these reactions, relative to the fission probability, are known, a measurement of the amount of $^{238}$Pu or $^{240}$Pu following a nuclear explosion can indicate the fission-yield.

*Because nuclear testing is no longer performed, the accuracy of the cross-sections is of higher importance because these data constrain and define the accuracy of weapons code predictions, and therefore impact the confidence in predictive capability.*

***Fusion-Yield***

Determination of the fusion-yield is more difficult because the isotopes produced by neutron interactions with the fusion fuels are not readily discernable. Consequently, some elements or isotopes can be inserted as radchem detectors at various locations in a nuclear device. During detonation, these detectors are subjected to a short and intense flux of fission and possibly fusion neutrons. After the detonation, the radchem detectors and their long-lived activation products are retrieved from the underground explosion site and subsequently analyzed. Many of the reactions for these radchem isotopes have a neutron energy threshold. Neutrons below this threshold do not produce the reaction. Placing several elements with different thresholds into the device can infer the energy distribution of the neutrons by measuring the amounts of the reaction products. Computational models are then used to match observed amounts of isotopes to determine the energy distribution of the neutrons and to provide the fusion-yield value.

A large amount of high-quality radchem data exists from past underground nuclear tests but its use is limited by the lack of accurate knowledge of reaction rates. The neutron energy spectrum and the location of the radchem detector are time-dependent quantities; information can only be determined from computer simulation. The mean neutron energy incident on a radchem tracer element placed within the device being tested changes significantly during the explosion. At "early-times" the spectrum tends to be very energetic, and reactions with a high-energy threshold such as (n, 2n) are possible. After the explosion, or at "late-time," the neutron spectrum has degraded to lower energies where reactions such as (n, $\gamma$) dominate. A basic ingredient in the analysis of data from radchem detectors is accurate knowledge of the energy-dependent activation cross-sections of these detectors.

Because of the intense neutron fluxes in a nuclear explosion, tracer elements can undergo a series of nuclear reactions that transform them from the stable radchem isotopes to other isotopes, which often are unstable. Through the recovery of debris from the nuclear explosion, these radioactive elements can be identified and quantified to give designers detailed information on performance of the nuclear device. But again, accurate reaction probabilities are required to completely interpret the results.

For example, when the stable isotope $^{169}$Tm is used as a radchem detector, the (n, 2n) reaction results in the production of $^{168}$Tm, which is an unstable isotope with a ninety-three-day-half-life. This radchem tracer was measured during the test program. A complication in interpreting the results of $^{168}$Tm production is this—in the nuclear device environment, neutrons can "down scatter" to produce copious quantities of low-energy neutrons. At low neutron energies (and generally later in time), neutron capture, where a neutron is absorbed into the nucleus, is the dominant nuclear reaction. Neutron capture reactions can modify the isotopic distributions created from the (n, 2n) reaction, complicating the extraction of device yield. To accurately extract the device yield from radchem detectors a complex network of nuclear reactions must be analyzed and understood. In particular, the reaction rate on the unstable nucleus must be known. The reactions network is illustrated in Figure 1. Similar concerns exist for reactions on $^{235}$U, which has the additional complication of the fission channel.

After decades of nuclear reaction research, much is known about capture reactions that occur on stable nuclides, but little is known experimentally about reactions on unstable, radioactive species. In the case of unstable nuclei, the nuclear weapons design community has had to rely only on theoretical calculations of these reactions. However, the reaction probabilities for the low-energy neutron capture reactions that perturb the primary isotopic yields are very difficult to calculate accurately. Differences between experiment and theory, up to a factor of ten, exist for unstable nuclei. These reaction probabilities are sometimes empirically adjusted in the explosion codes to reproduce observed results. The modern ASC codes are attempting to simulate device performance based on scientific knowledge rather than adjusting quantities to fit empirical results. It is important for the mission that these adjusted quantities be accurately determined, eliminating "knobs" in the code. This can only be done with experimentally determined cross-sections.

*Uncertainties in the cross-sections directly impact the uncertainty of weapons code predictions of the isotopic ratios measured in past underground tests.*

## Requirements

The requirements for the Advanced Simulation and Computing codes (ASC) program are driven by the need for more accurate data to be included in upcoming releases of the codes and data libraries. The ASC L2 HiFi nuclear data library, to be released at the end of FY05, includes data for $^{239}$Pu(n, 2n) cross-section and iridium and yttrium radchem cross sections from recent LANSCE measurements. Additional data, including $^{234,236}$U capture for late-time studies, will be added as they become available.

Future releases of ASC codes in March of FY06 and FY07 will require additional LANSCE cross-section data for:

- Americium isotope capture cross-section for plutonium diagnostics (DANCE detector),
- Prompt neutron and gamma fission spectra for plutonium and uranium isotopes (FIGARO detector),
- Capture cross-sections for stable & unstable actinides, for late-time studies (DANCE),
- Fission cross-sections on small samples of unstable isotopes ($^{240}$Am, $^{235}$mU, etc.) for production-depletion inventories, lead slowing-down spectrometer (LSDS),
- Radchem cross-sections for thulium, arsenic, iridium, and tungsten,
- Neutron inelastic scattering on plutonium for diagnostics, and
- Precision thermonuclear cross-sections for lithium-6.

Beyond FY07, ASC codes will require further improvements, based upon more accurate data, in cross-sections for both fissile material and radchem tracers to meet the Predictive Capability milestones established at both LANL and LLNL. By increasing the beam intensity at LANSCE, the measurements will be executed more rapidly and with higher accuracy. Improvement in beam intensity will be "mission enabling" for the goal of measuring reaction cross-sections on short-lived isotopes.

The partnership between LANL and LLNL over the past few years, such as hosting the Weapons Nuclear Data Conference in 2002, resulted in the nuclear data program utilizing LANSCE facilities to meet requirements from both laboratories. Figure 2 displays a roughly prioritized list of the radchem tracers that were used in past UGTs by both LANL and LLNL. The figure shows the stable isotopes implanted in the nuclear devices in blue. The yellow isotopes are those radioactive "daughters" that are generated in the explosion with cross-sections that can be measured using an upgraded LANSCE. Currently, most of the yellow isotopes have little if any measured data.

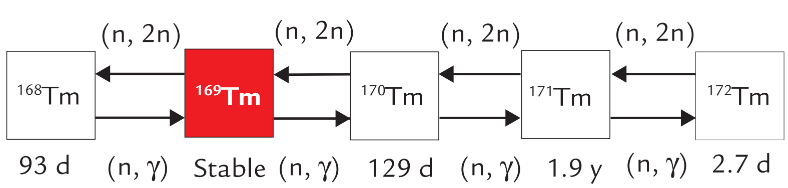



**Figure 1.** Simplified reaction network for neutron-induced reactions on $^{169}$Tm.

## Short-lived Radioactive Target Production and Experiments

The frontier of nuclear physics is studying nuclear reactions on unstable targets. The basic nuclear physics interest centers on studying properties of the nucleus and the nuclear force in systems with ground-state parameters (spin, isospin, etc.) that are different from the limited range available in stable nuclei.

There are also many related areas of physics that require accurate cross-sections on unstable nuclides for particular applications, such as stellar nucleosynthesis. The importance to nuclear astrophysics is discussed in *Chapter 5: Fundamental Nuclear Physics Research*.

The need for studies on unstable nuclides is recognized by the Nuclear Science Advisory Committee, which gives the proposed Rare Isotope Accelerator (RIA) its highest priority. *(See Appendix E: The Rare Isotope Accelerator {RIA}.)* While the RIA facility will be required for highly unstable nuclear reaction studies, LANSCE produces short-lived radionuclides used for important experiments, today.

The isotopes of interest to the radchem program are shown in Table 1, along with the time to produce $10^{18}$ atoms of material. What is needed, however, is to build on-site handling and separation facilities ("hot cells") to purify and fabricate the irradiated material into finished targets. Many other nuclides needed for radchem studies can be produced by thermal-neutron capture reactions. Examples are $^{46}$Sc, $^{95}$Zr, $^{108}$mAg, $^{110}$mAg, $^{170}$Tm, $^{171}$Tm, $^{185}$W and $^{192}$Ir. However, there are few reaction irradiation facilities operating in the United States. LANSCE can re-establish this capability. The irradiation port at the Lujan Center could provide a reactor-equivalent flux of about 7 x $10^{12}$ n/cm$^2$/sec. This will be adequate to produce $10^{18}$ atoms of $^{170}$Tm from 1 gram of $^{169}$Tm in twenty-four days. An irradiation port at the proposed LANSCE-MTS could provide a neutron flux estimated to be 100 times that currently available at the Lujan Center.

Although some of the isotopes produced by neutron irradiation could be separated from the target material chemically (following beta decay), most would require the Radioactive Species Isotope Separator (RSIS) currently located at LANL. The RSIS needs to be relocated to LANSCE to facilitate material handling and transfers.

Other nuclei of interest require hot cell purifications, for example $^{177m}$Lu and $^{182}$Ta, by spallation on tungsten or other targets in the direct 800 MeV proton beam.

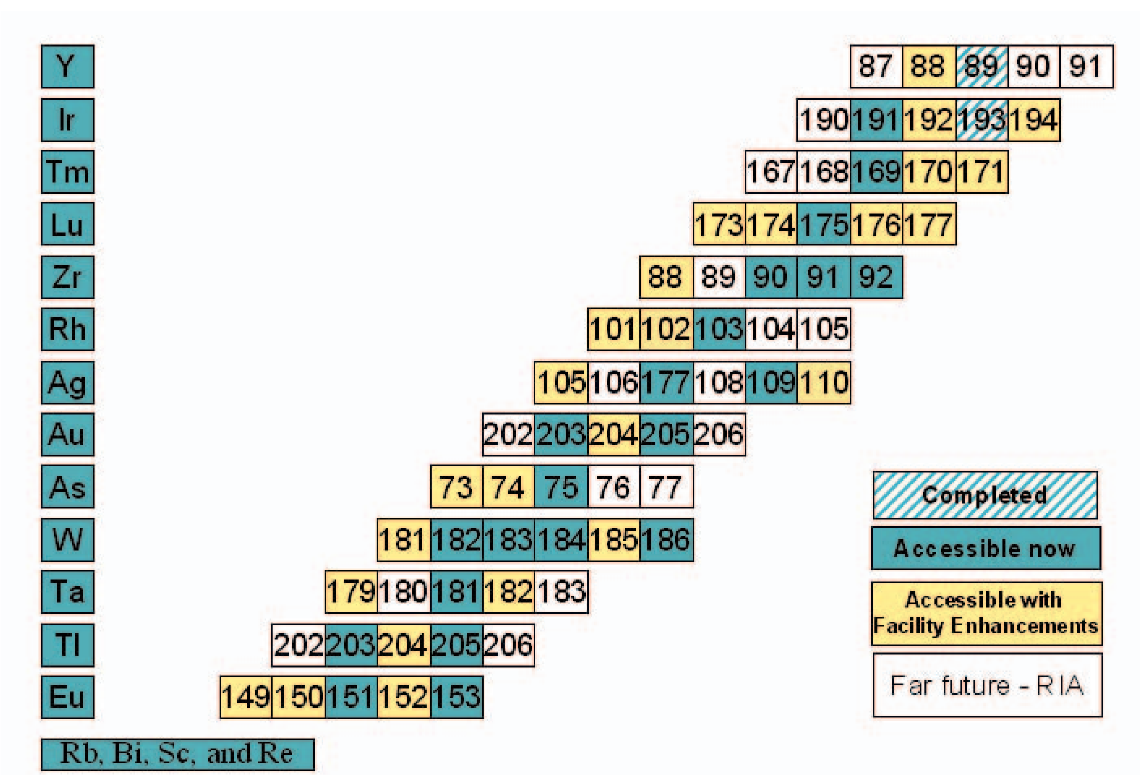



**Figure 2.** List of radiochemical tracers used in LANL and LLNL underground nuclear tests, along with the radioactive "daughters" generated in the explosion. The yellow isotopes represent those that have reactions targeted for measurement in the upgraded LANSCE facility.

| TABLE 1: ISOTOPE PRODUCTION AT THE ISOTOPE PRODUCTION FACILITY | | | |
|---|---|---|---|
| **Isotope** | **Time to Produce $10^{18}$ Atoms (Days)** | **Isotope** | **Time to Produce $10^{18}$ Atoms (Days)** |
| $^{73}As$ | 10 | $^{157}Eu$ | 10 |
| $^{83}Rb$ | 4 | $^{158}Eu$ | 12 |
| $^{88}Y$ | 10 | $^{174}Eu$ | 70 |
| $^{101}Rh$ | 10 | $^{179}Eu$ | 10 |
| $^{105}Ag$ | 20 | $^{181}Eu$ | 6 |
| $^{149}Eu$ | 45 | $^{195}Eu$ | 10 |
| $^{150}Eu$ | 20 | $^{207}Eu$ | 10 |

*An irradiation port at the proposed Materials Test Station could provide a neutron flux estimated to be 100 times that available at the Lujan Center.*

The existing DANCE detector at the Lujan Center is a state-of-the-art gamma-ray detector designed to make neutron capture measurements on small (~1 mg) samples of radioactive material. The high-efficiency, energy resolution, and nearly 4π solid angle, mean that DANCE will measure the summed energy of all gamma-rays emitted following a neutron capture. This implies that the capture event can be discriminated from interfering backgrounds with much higher efficiency than in earlier measurements. The combination of DANCE, the high neutron fluxes available at the Lujan Center, and the proposed chemistry upgrades, will produce a capability to capture measurements on radionuclides unique in the world, and ensure that LANSCE remains at the forefront of nuclear research with short-lived isotopes.

The neutron energy range of interest for these studies is the same as that needed for measurements relevant to nucleosynthesis and nuclear astrophysics, as discussed in *Chapter 5: Fundamental Nuclear Physics Research.* Methods to increase the neutron flux at the Lujan Center by factors of ten to 100 times are discussed there. An increase of neutron flux will have similar benefits to the radchem program by enabling measurements on targets with shorter half-lives.

*The combination of DANCE, the high neutron fluxes available at the Lujan Center, and the proposed chemistry upgrades, will produce a capability to capture measurements on radionuclides unique in the world, and ensure that LANSCE remains at the forefront of nuclear research with short-lived isotopes.*

## NEUTRON RADIOGRAPHY FOR ACCURATE AND NON-DESTRUCTIVE COMPONENT SURVEILLANCE

### Background

Nuclear weapon performance is affected by a number of structural and chemical anomalies: assembly defects and misalignments, corrosion, cracking, and other aging effects. Nondestructive inspection methods are useful for examining both stockpile systems and research test assemblies. Traditional methods such as x-ray and gamma-ray radiography yield detailed views of the high-Z metallic components, but lack sensitivity to embedded low-Z components and hydrogenous material, and have difficulty penetrating the thickest objects. Neutron radiography can provide highly complementary and, in some cases unique views of the internal light-element features. Fast neutrons (E > 1 MeV) are highly penetrating and are well suited for examining warhead-size objects.

In contrast to fast-neutron radiography, thermal (cold) neutron beams are best suited for relatively thin objects. Because of the smaller interaction volume in the detection process, thermal beams offer higher spatial resolution than fast neutrons, potentially in the few-micron range. Such beams are particularly good for mapping trace hydrogen concentrations or detecting cracks in hydrogenous material, such as firing sets, gaskets, o-rings, and similar material.

LANL currently lacks a dedicated neutron-radiography facility. Both fast-neutron and thermal-neutron radiography capabilities are needed to service the needs of the weapons program, and will have beneficial civilian applications as well. The broad spectrum and pulsed beam of spallation neutron sources make it easy to exploit, in a single facility, both the isotopic and energy dependence of thermal neutrons and the high penetrability of fast neutrons.

Three current stockpile stewardship applications for static fast-neutron radiography are currently being investigated:

1) Specific stockpile issues have been identified that require the ability to image features in hydrogenous layers shielded by high-Z material. Fast neutrons offer a potential solution. The technical challenge for this application is to produce a large beam (> 30 cm) in a specific energy region (2 – 14 MeV), with enough intensity (> $10^7$ n/cm$^2$/s) to inspect a large number of systems in a reasonable amount of time. Two imaging strategies are proposed, one of which has been successfully demonstrated with a 14 MeV beam from a commercial deuterium-tritium neutron generator. This project highlighted the need for intense compact fast-neutron sources.

2) Organic hydrogen-getters are used as anti-corrosion elements in some stockpile systems. Neutron transmission measurements offer a non-destructive method for evaluating hydrogen-getter saturation. The degree of saturation is an indicator of the remaining useful life of the component in which the getter is embedded. LANSCE tested measurement techniques with both epithermal and fast neutrons. The radiographic and time-of-flight measurements clearly demonstrate the ability of neutron transmission measurements to distinguish between materials with varying hydrogen densities. LANSCE is continuing with development of a dual-energy or dual-beam measurement technique that will maximize sensitivity to hydrogen content and minimize sensitivity to sample thickness variations. One potential dual-beam method involves simultaneous or sequential interrogation with both x-rays and neutrons.
3) Hydro-test assemblies are meticulously constructed, measured, and documented. But geometrical deviations from the design specifications can arise from compression, rotation, and other stresses during the assembly process. Gamma-ray radiography currently offers the most convenient non-destructive inspection method, yet this technique is only sensitive to the heavy-metal components and current gamma-radiography facilities do not provide beams large enough to illuminate the entire assembly in one exposure. Fast-neutron beams could provide valuable complementary information. Fast neutrons are sensitive to lower-Z elements, providing a more complete picture of the internal status of the assembly, and can easily be made large enough to allow for 3-D tomographic inspection, something not possible with existing gamma-ray sources.

*Both fast-neutron and thermal-neutron radiography capabilities are needed to service the needs of the weapons program, and will have beneficial civilian applications as well.*

### Requirements

No existing beamlines at LANSCE's Lujan Center or Weapons Neutron Research (WNR) facility currently possess all the characteristics required for full development of the applications outlined above. The necessary characteristics include a target and flight path capable of sub-millimeter resolution. In addition, experimental area shielding must be capable of accommodating thick objects, while safety (high-explosives), and security issues (secret restricted data {SRD} material) must be addressed. No other facilities outside of LANL can meet these requirements. Upgrading to these specifications will provide a capability that will satisfy national missions and LANL's missions.

A fast-neutron fluence of approximately $10^{10}$ n/cm$^2$ is required to produce a statistically good image. The WNR flight paths currently deliver about $10^6$ n/cm$^2$/s, which translates into a several-hour exposure. This long exposure time makes it difficult to do high-fidelity tomography, which requires hundreds of images in a short amount of time. An order-of-magnitude-increase in neutron intensity is required.

A cost-effective first step would involve upgrading a WNR beam line with a new shutter and experimental station specifically designed to handle high-explosives, special nuclear material (SNM), and SRD material. A new variable-aperture shutter, collimation, and sweep-magnet system will also be required. The energy spectrum on this beamline is not optimal (93 MeV mean energy) for all potential applications, but this would provide a relatively low-cost (< $1M) upgrade capable of meeting most of the requirements for continued detector development and proof-of-principle measurements involving small numbers of images. For example, full-view radiographs of hydro-test assemblies could be obtained with such an upgraded flight path.

The next step involves taking advantage of the MTS target development at LANSCE. A fast-neutron-beam-port on this target could potentially provide the order-of-magnitude increase in neutron flux required to implement high-fidelity 3-D tomography. A second moderated beam line could provide thermal neutrons for thin-sample studies. These beam lines would provide first-class neutron-radiographic capabilities. The addition of an x-ray and stand-alone monoenergetic neutron source would create a radiographic facility capable of multispectral analysis; the radiographic equivalent of color photography. Advanced neutron imaging detector development can take place concurrently with beam line development. The goal of such development is to produce efficient time-gated detectors with spatial resolution of a few tens of microns.

The WNR beam line upgrade is a one-year project. The installations would be coordinated with MTS construction. Upon completion, such a facility would provide unprecedented multi-spectral analysis capability with premier flux and resolution.

*No other facilities outside of LANL can meet these requirements. Upgrading to these specifications will provide a capability that will satisfy national missions and LANL's missions.*

## RADIATION EFFECTS ON ELECTRONICS

### Background

Sandia National Laboratories has the responsibility of ensuring the survivability of the electronics packages in nuclear weapons in intense radiation environments. In the past, the qualification of electronic parts was performed using the neutron fluxes from the Sandia Pulsed Reactor (SPR). Because this pulsed reactor is being decommissioned, an alternative radiation source for qualifying parts for nuclear weapons systems is needed. It appears that with an upgraded facility, neutron beams generated by the intense proton pulse from the proton storage ring (PSR) at LANSCE will meet the qualification requirements that are presently being addressed by the SPR reactor.

LANSCE now delivers approximately 4 x $10^{13}$ protons/pulse from the PSR to WNR for radiation effects measurements. This produces approximately 5 x $10^{12}$ neutrons/$cm^2$ in a volume near the neutron production target. Sandia National Laboratories scientists indicate that, with a factor of ten increase in neutron intensity, the LANSCE facility should be able to meet the requirements of the SNL certification program that currently rely on their SPR.

*Sandia National Laboratories scientists indicate that, with a factor of ten increase in neutron intensity, the LANSCE facility should be able to meet the requirements of the SNL certification program that currently rely on their SPR.*

## Requirements

The specifications of the SPR reactor, compared to the current LANSCE capability and with LANSCE enhancements are listed in Table 2. Table 2 also shows that the pulse width of the current LANSCE source is significantly narrower than the pulse width from the SPR reactor. This narrow pulse will open new opportunities for looking at short-time annealing of transistor gain, opportunities not possible using the SPR reactors.

**Table 2. Compares SPR to LANSCE's current capability and to LANSCE-E.**

| | SPR | LANSCE | LANSCE Enhancements |
|---|---|---|---|
| Neutron intensity in pulse (n/$cm^2$/sec) | $10^{14}$ | 6 x $10^{12}$ | 4 – 8 x $10^{13}$ |
| Pulse duration (FWHM) | 76 µsec | <1 µsec | ~1 µsec |
| Mass of $^{235}$U (kg) | 216 | 0 | 0 – 10 |

The LANSCE source presently provides approximately 5 x $10^{12}$ n/$cm^2$/pulse. With modest enhancements, LANSCE-R will increase the neutron intensity as follows:

- A factor of two by increasing the output of the $H^-$ ion source.
- A factor of two by improving the transport from the PSR to WNR.
- A factor two to four by installing a depleted uranium target or boosted target.

*Improving LANSCE's neutron intensity by a factor of eight to twenty meets the requirements for researching electronics parts qualifications.*

Improving LANSCE's neutron intensity by a factor of eight to twenty meets the requirements for weapons electronics parts qualifications.

# PROMPT DIAGNOSTICS CALIBRATION

## Background

Prompt diagnostics includes measurements of neutrons, gamma-rays and x-rays. Time-dependent spectral and spatial experiments produce data that put tight constraints on computer models. In the days of underground nuclear tests, these data were combined with radiochemical results to infer explosion yields, radiation output, and detailed performance of devices. Now the nuclear tests are limited to subcritical experiments ("subcrits") at the nuclear test site (NTS) and inertial confinement fusion experiments at the national ignition facility (NIF) and Omega lasers, and at the Sandia Z Experiment. LANSCE's role in developing prompt diagnostics will be greatly strengthened with improvements in beam characteristics that include more intense single-pulse beams on optimized targets and for continuous experiments, more protons per micropulse with a higher duty factor.

Many of the scientists and engineers who performed prompt diagnostic experiments in the test program that halted in 1992 have retired. New people have been hired, but there is not enough field experience to train new personnel. LANSCE upgrades will allow new scientists and engineers training in prompt diagnostics.

During the nuclear testing era, LANSCE was used to calibrate threshold experiment (THREX) detectors with the micropulse beam. LANSCE built a beam line at WNR to characterize and calibrate the solid-state detectors used in THREX packages.

In addition, since testing ended, new techniques and instrumentation were developed over the last decade. These new techniques and instruments will need testing, and must be commissioned and analyzed for confidence. An intense single-pulse neutron source based on an optimized target driven by the LANSCE-PSR will provide the test bed to develop these new techniques.

## Requirements

LANSCE is a unique facility in the LANL/LLNL/SNL complex for characterizing and calibrating neutron and gamma-ray detectors. Detectors for subcritical experiments need to be more sensitive than the THREX and NeUtron EXperiment (NUEX) detectors, used for past tests of nuclear explosives. With a large single pulse of radiation from WNR, the time dependence of the detectors will be characterized. Features such as “late light” from scintillators will be quantified. These new capabilities will get the prompt diagnostic personnel interested again in using an accelerator for training, testing, characterizing and calibrating, as a single-pulse source mocks up the field experience. An optimized target assembly driven by increased single pulses from the PSR will be ideal for this work. There is no other facility in the weapons laboratories that will provide the energy range, pulse widths, and the flexibility of providing pulses on demand.

*New prompt diagnostic techniques and instruments will need testing, and must be commissioned and analyzed for confidence. An intense single-pulse neutron source at LANSCE will provide the test bed to develop these new techniques.*

## ENHANCED NUCLEAR SCIENCE FACILITIES FOR WEAPONS AND BASIC SCIENCE RESEARCH AT 800 MEV

Enhancements to LANSCE will improve the nuclear physics research conducted at the Lujan Center and WNR. Three aspects of these facilities will be improved:

· Beam Capabilities,

· Facility Infrastructures, and

· Instrumentation.

These improvements will yield (depending on application) a factor of two to twenty times increase in neutron intensity, the ability to operate multiple experiments in a non-interfering manner, and the ability to satisfy the mission requirements for weapons nuclear data and electronics parts qualifications.

Specific Enhancements include:

1) ***WNR Fast Neutrons:*** For WNR research, the rate of data acquisition depends on the neutron flux. At present, LANSCE uses 100 Hz macropulses from the accelerator with a macropulse length of 625 microseconds, composed of micropulses with a spacing determined by experimental requirements. Future enhancements will increase the macropulse length and the data rate will improve proportionally.

2) ***Lead Slowing-Down Spectrometer (LSDS):*** LANSCE demonstrated the capability of measuring fission cross-sections on very small samples, (10 ng). The LSDS is assembled in WNR for each run and then disassembled a day or two afterwards. The radiation exposure to personnel is within limits—but could be much lower. Also, the lead is pure and soft and assembly-disassembly results in a steady deterioration in the condition of the constituent lead blocks (impurities in the lead, like oxides, degrade spectrometer performance). LANSCE enhancements will provide an area where the LSDS will be installed permanently and will increase the LSDS size from twenty tons to 100 tons, similar in size to the LSDS at the Moscow Meson Factory. The quality of the data will be greatly improved.

3) ***Sample Preparation Facility:*** This facility will provide a facility for preparing radioactive samples, and an area with glove boxes, hoods, etc. to perform the required chemistry for sample preparation. In addition, it will allow separations necessary for samples, such as the twenty-six-minute isomer of $^{235}$U produced by the decay of $^{239}$Pu.

4) ***Neutron Radiography:*** This will entail upgrades in the WNR beamline with a new shutter and experimental station. The energy spectrum on this beam line (93 MeV mean energy) will provide a relatively low-cost capability for detector development and proof-of-principle radiography measurements.

5) ***GEANIE Enhancements:*** This array of twenty-six gamma-ray detectors is a key capability for Weapons Nuclear Research. To address future requirements, it will be upgraded in number and size (increased gamma-ray efficiency) and to perform gamma-gamma coincidence experiments. Neutron inelastic scattering from actinides is extremely difficult to measure accurately and is very important for proper neutron transport calculations. An upgraded GEANIE detector array, with enhanced neutron beams at the WNR facility will enable the accurate measurement of cross-sections using thin targets.

6) ***FIGARO Enhancements:*** This will provide the full complement of fifty detectors to achieve maximum performance. Measurements of fission neutron spectra with smaller samples to improve the quality of the data, with actinides that are difficult to handle, and with higher resolution using a longer sample-detector flight path length, become possible. Upgrading FIGARO with more neutron detectors and increased neutron flux allows measurements on the $^{239}$Pu (n, 3n) cross-section. These cross-section data are necessary to increase the accuracy of the crucial $^{239}$Pu(n, 2n) reaction diagnostic.

***7) Pulsed Radiation Source:*** Facility enhancements will:

1) Increase output of LANSCE $H^-$ ion source, which should approximately double the source intensity.
2) Improve the beam transport from the PSR to WNR by a factor of two.
3) Improve the neutron production target (candidates range from depleated uranium to enriched uranium) by a factor of two to five.
4) Provide a new experimental area allowing dedicated low-duty factor use of the PSR beam. This new area can be used for a wide range of experiments including LSDS, neutron resonance spectroscopy, high-power target development, and radiation effects.

## SUMMARY

Future LANSCE enhancement will meet the missions by improving nuclear science and the physics certification of nuclear weapons in the following three ways:

*1) Improving the data required to accurately predict device performance, including:*

- *High-precision-cross-section measurements of the energy producing fission reactions (including isomeric states),*
- *The reactions on, and the properties of, fission products, and*
- *The measurements of fission outputs, including neutron and γ-ray spectra, and charged particle products.*

*2) Generating nuclear data important for interpreting the performance of past underground tests, in particular, the (n, xn) and (n, γ) reactions that are part the radchem diagnostic reaction networks. A significant number of these reactions include isotopes that are radioactive and heretofore have not been measured.*

*3) Generating nuclear data used as inputs to computer modeling codes. These data will be used to predict nuclear properties of isotopes that cannot otherwise be measured.*

*4) Providing a capability for weapons effects testing.*

### WEAPONS NUCLEAR SCIENCE: WEAPONS

| Program/Science | Requirements | LANSCE ENHANCEMENTS |
|---|---|---|
| | | |
| Isotope Production and Cross-section Measurement | Producing and measuring unstable isotopes for:<br>· Radchem assessment, and<br>· Quantifying fission and fusion energy production. | Significant capability to produce proton-rich isotopes by IPF and measure cross-section at WNR and Lujan Center.<br>Proposed enhancements include:<br>· Isotope handling improvements. Increased peak neutron flux at WNR and improved capability to produce and measure unstable isotopes.<br>· MTS enables neutron-rich production of unstable isotopes.<br>Meets future requirements. |
| Nuclear Weapons Data | Accurate measurement of weapon relevant cross-sections for ASC code development. | Increased flux at WNR, enhances capability for measuring cross-sections on smaller samples, actinides, and unstable isotopes.<br>Meets future requirements. |
| Nuclear Weapons Effects Testing:<br>SPR Mission | $1.0 \times 10^{14}$ n per pulse @ 76μs FWHM | $1.0 \times 10^{14}$ n/cm$^2$ per pulse @ 1μs FWHM<br>Meets SPR requirements. |

## WORKSHOP ON GLOBAL NUCLEAR FUTURES AT LANSCE: NATIONAL SECURITY AND DEFENSE APPLICATIONS, INDUSTRIAL RESEARCH OPPORTUNITIES, AND EMERGING NUCLEAR PHYSICS

**August 22-24, 2005**
**Fairmont Hotel, Washington DC**

*To gather information and recommendations from the LANSCE user community, regarding the refurbishment and the future evolution of LANSCE, the Los Alamos National Laboratory invited key user representatives to a workshop: Global Nuclear Futures at LANSCE.* Invitees were charged with focusing on the role that accelerator science plays in addressing challenges for the national and global nuclear future—with a special interest in national security and defense applications, industrial research opportunities, and emerging nuclear physics.*

## NUCLEAR PHYSICS AND NATIONAL SECURITY AND DEFENSE

**Key Issues Discussed**

To successfully design nuclear weapons or nuclear reactors, to assess radiation effects, and to calculate potentially critical systems for safety analyses, a wide range of nuclear information, "nuclear data," is required. Experiments at LANSCE generate accurate nuclear data and, in some cases, allow experimental measurements of quantities that formerly could only be calculated by nuclear theoretical models, models that have significant uncertainties.

In nuclear weapons research, the emphasis is on understanding the Quantification of Margins and Uncertainties (QMU). The QMU is needed to enable quantitative assessments of the performance of a weapon over its lifetime. Uncertainties in the nuclear data will dominate the uncertainties in weapon performance. Thus, it is essential that uncertainties in the nuclear data be reduced. The data in question are those of the energy-producing reactions, and in the diagnostic reactions, used to interpret the data from nuclear tests conducted until 1992. Because there have been no tests since then, these benchmark data are the only constraints on present designs and design codes. Present requirements are for experimental measurements of fission reactions on fuel actinides, as well as impurities, neutron-capture reactions on radio-chemical materials used to diagnose the performance of the weapon, and reactions on light nuclides. These requirements change from year-to-year and, therefore, the capability of making new measurements in a timely way is essential to the nuclear program.

A refurbished and upgraded LANSCE will be the world-class facility for nuclear physics, with neutrons and nuclear data for applied programs. Future requirements of these programs will include much more accurate cross sections, such as for fission reactions, data on radioactive isotopes (where nearly no experimental data exist now), much better information on radiations emitted in nuclear reactions, and studies of the basic competition between different reaction mechanisms. This latter information is necessary for improving our basic knowledge of nuclear reactions, so that important reactions that cannot be measured (because of lack of suitable material, high radioactivity, and/or toxicity) will be calculated with increased confidence in the nuclear models and in computer codes. Improved capabilities at LANSCE are essential to meet the programmatic requirements with accuracy and efficiency.

***Improved Instrumentation***

Improvements in instruments should be part of any upgrade. The present suite of instruments needs improvement. The cost of these improvements would be small compared with the accelerator upgrade costs, but the returns would be very large.

***Radioactive Materials and the Isotope Production Facility***

The future of neutron-nuclear physics will require radioactive targets. Nearly all of the current information on nuclear reactions comes from experiments with stable targets. What happens in reactions with nuclei off the valley of stability is unknown. Yet, these reactions are of great importance to understanding the performance of nuclear weapons, to assessing the possibilities for transmutation of nuclear waste, and to basic models of the formation of the elements in stars. Accordingly, the LANSCE Isotope Production Facility should be enhanced, and the Materials Test Station completed, to ensure the production of unstable isotopes for use in research, industrial, and national security applications.

## RADIATION EFFECTS IN SEMICONDUCTORS

**Key Issues Discussed**

The session was primarily devoted to the study of neutron radiation effects in semiconductor components—neutrons that are produced in the atmosphere by cosmic rays are currently thought to cause the greatest number of failures in semiconductor devices. This failure mode is equal to all other failure modes combined. Because neutrons are uncharged, they can affect semiconductors in space, in aircraft, and on

* For the complete workshop report, see Global Nuclear Futures at LANSCE: Fifth in a Series of Workshops Exploring the Future of the LANSCE Facility at Los Alamos National Laboratory, August 22-24, 2005, Fairmont Hotel, Washington DC, Christensen, D., et al., Los Alamos National Laboratory, LA-UR- 05-7330, 2005.

or in the ground. These energetic neutrons interact with the material in the semiconductor device and produce charged particle reaction products, or recoils, and can cause failures. These failures range from nondestructive failures such as single-event upsets (SEU), to destructive failures such as latchups. For example, the reaction can change a bit from a “0” to a “1” or the reverse. A recurring theme was the unequivical need for semiconductor testing at LANSCE. It is generally felt that as semiconductors get smaller, and as the number of nodes increase and the voltages decrease, semiconductor devices will become more susceptible to neutron-induced failures.

Currently, there is no industry-wide standard for SEU testing. Every computer manufacturer must specify its own requirements that the semiconductor manufacturer must meet. In addition, because there are no standards, even if a part meets some acceptance criteria now, the manufacturer may change the process and alter the part’s performance in the future.

The semiconductor industry recognizes these problems and is working towards developing a standard for semiconductor testing—testing at WNR is the “preferred” method of testing because it most closely, and unambiguously, tests the performance of the semiconductor in the field. The WNR facility will play an important role in developing, implementing, and providing a test bed for such a standard. In addition, participants raised the concern that LANSCE must be able to handle future testing demand.
All the participants were enthusiastic about LANSCE maintaining the capability, and improving its capability, to test semiconductor parts at the Weapons Neutron Research facility.

Regarding Defense Programs applications, Sandia National Laboratories’ scientists plan to continue using the WNR facility as a key part of their radiation effects program.

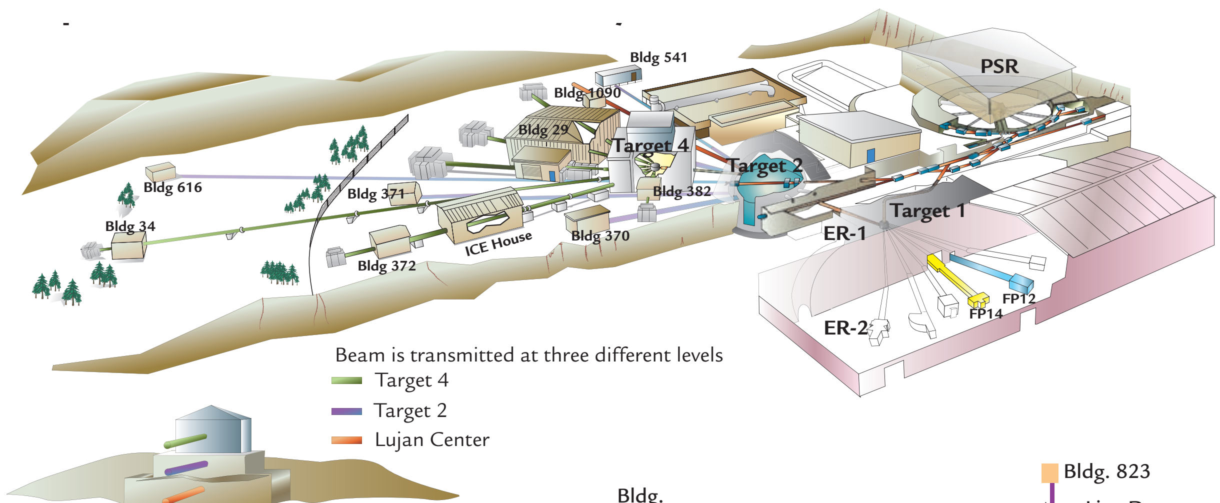
## KEY WORKSHOP OUTCOMES AND RECOMMENDATIONS INCLUDE:

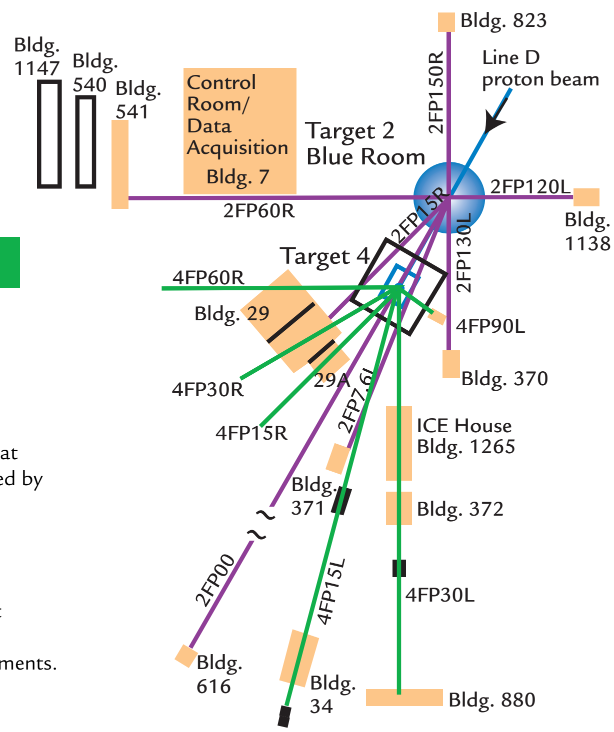
1. It is strongly recommended that LANSCE refurbishment (LANSCE-R) proceed to ensure beam reliability and availability. This is critical for defense program applications, physics research, isotope production and research, and industrial semiconductor quality testing.
2. It is highly recommended that the Materials Test Station be constructed. Finally, the use of parasitic neutrons for isotope production is highly recommended.
3. It is highly recommended that enhancements beyond LANSCE refurbishment take place to double the beam current. A further increase in beam energy to 3 GeV will increase the flux by a factor of five, making the MTS useful for accelerated testing of fuels, materials, semiconductors, and so forth.
4. It is unanimously stated by industry that WNR is the preferred industrial location to test semiconductor devices. The industrial expectation is that semiconductor testing requirements will increase exponentially in the future.
5. To address the issues specific to semiconductors in defense program applications, it is highly recommended that the ion source output should be increased—by at least a factor of two. The LANSCE enhancements should provide the Sandia National Laboratory radiation experiments and the Lujan Center experiments to operate simultaneously and on-demand.
6. It is highly recommended that instrumentation be enhanced. Improvements in detectors, electronics, and data acquisition with the present LANSCE beams will result in large improvements in experimental capabilities and productivity both for nuclear data and for nuclear physics.

**Participants**
Robert Bauman, Texas Instruments
John Becker, Lawrence Livermore National Laboratory
Barry Berman, George Washington University
Allan Carlson, National Institute of Standards and Technology
Mark Chadwick, Los Alamos National Laboratory·
Michael Dunn, Oak Ridge National Laboratory
Joe Fabula, Xilinx
Steven Grimes, Ohio University
Robert Haight, Los Alamos National Laboratory
Richard Hess, Honeywell
Calvin Howell, Duke and Triangle Universities Nuclear Laboratory
Paul Koehler, Oak Ridge National Laboratory
Norm Kolb, Sandia National Laboratory
Austin Lesea, Xilinx
Eugene Normand, Boeing
Pavel Oblozinsky, Brookhaven National Laboratory
Steven Wender, Los Alamos National Laboratory

*Authors:*
*Michael W. Cappiello*
*Dana C. Christensen*
*Robert C. Haight*
*Allen Hartford, Jr.*
*Eugene J. Peterson*
*Stephen A. Wender*

## WEAPONS NEUTRON RESEARCH FACILITY




### Target 4 Flight Paths (FPs)

**4FP90L** This FP is used to measure neutron-proton-capture cross-sections important for understanding "Big Bang" nucleosynthesis.

**4FP30L** This FP has two experimental stations. The first station is at approximately 20 m from the production target and is used by industry, universities, and other national labs to measure neutron-induced failures in semiconductor devices.

**4FP15L** This FP provides the highest neutron-energy resolution. At present, the approximately 90 m long FP is being used for dosimetry, neutron transport, and neutron-spectra experiments.

**4FP15R** The (n,d) scattering experiments, which use a liquid-hydrogen target, are located on this approximately 18 m long FP.

**4FP30R** Most recently, experiments on this approximately 20 m long FP studied neutron-induced reactions for nuclear-level-density studies and neutron-induced fission and gas production in structured materials.

**4FP60R** The GEANIE spectrometer consists of approximately twenty-six Compton-suppressed, high-resolution germanium γ-ray detectors and is located on this approximately 20 m long FP. The GEANIE instrument is used to address issues of nuclear structure, spectroscopy, and cross-section measurements for both stockpile stewardship and basic science.

### Target 2 (Blue Room) Experiments

In neutron resonance spectroscopy, the PSR beam is used to produce an intense single pulse of neutrons for measuring the temperature and particle velocities of dynamic systems at different times during their evolution. The temperature is obtained by measuring the Doppler broadening of low-energy neutron resonances.

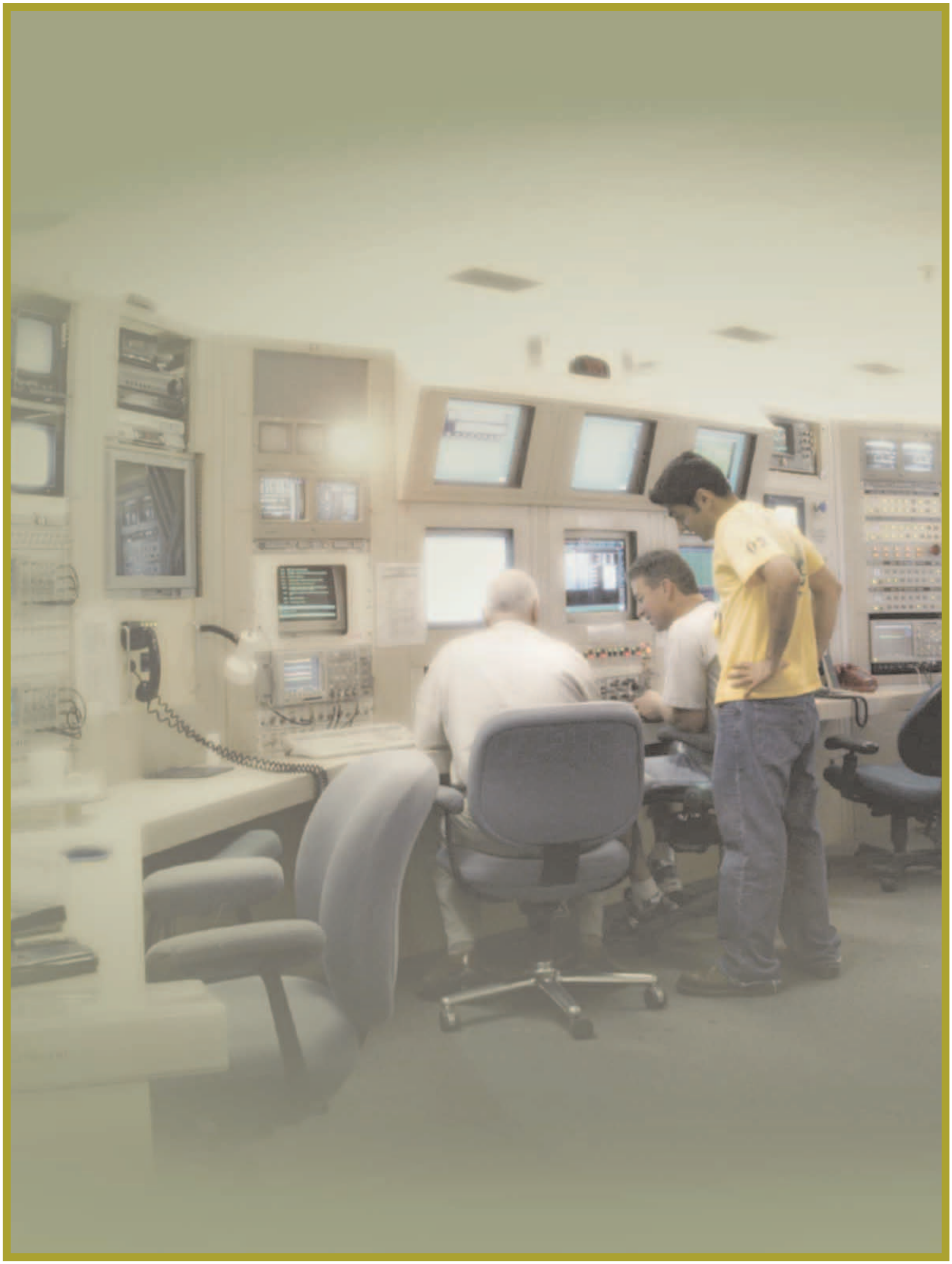
Single pulses from the PSR beam are used to study the shock induced by the incident beam on a liquid-mercury target for the SNS.

# Chapter 5

## Fundamental Nuclear Physics Research

J.D. Bowman, *P-23*
G.B. Mills, *P-25*
G.S. Mitchell, *P-23*
R. Reifarth, *LANSCE-NS*
A. Saunders, *P-25*
W.S. Wilburn, *P-25*

THE CENTRAL CONTROL ROOM AT LOS ALAMOS NEUTRON SCIENCE CENTER



# Fundamental Nuclear Physics Research

## ABSTRACT

Los Alamos Neutron Science Center (LANSCE) and Los Alamos National Laboratory (LANL) are centers of scientific excellence and productivity in nuclear science because they nurture the synergy of fundamental nuclear physics research with applied programs. LANSCE enhancements provide LANL the ability to evolve with, and catalyze further evolution in, fundamental nuclear physics research and applied nuclear physics. LANSCE will continue as a world leader in scientific research excellence and productivity.

## INTRODUCTION

LANSCE-based research in fundamental nuclear physics plays an important role in ensuring that the Department of Energy (DOE) and the National Nuclear Security Administration (NNSA) fulfill their missions. Its advanced facilities and internationally recognized staff and users keep LANL at the forefront of nuclear physics research. By continually performing world-class research LANSCE increases the mutually beneficial interaction between LANL scientists and other world leaders in fundamental nuclear physics, attracts top scientific talent to the Laboratory, and enhances the skills of its scientific staff.

Fundamental nuclear physics research at LANSCE spans four major areas: cold neutrons, ultracold neutrons (UCN), neutrinos, and nuclear astrophysics. (The possibility of building a rare isotope accelerator (RIA), while not considered as one of the upgrade paths, is discussed in *Appendix E: The Rare Isotope Accelerator*.) Cold and ultracold neutron sources, with enhanced capabilities, will provide improved precision tests of the standard model of the electroweak interaction. An enhanced pulsed neutrino source, driven by a megawatt-class proton beam, will create a highly productive facility for studying the masses and mixing parameters of neutrinos, and create a unique research facility in the U.S. Enhanced capabilities for studying neutron capture on radioactive targets will greatly improve our understanding of nucleosynthesis in astrophysical processes. These enhanced capabilities will allow LANL to remain at the forefront of these areas in fundamental nuclear physics research for decades, and provide significant new capabilities to the scientific community.

Future challenges and opportunities in fundamental nuclear physics research will be met with the LANSCE enhancements under consideration. Planning documents generated by the nuclear and high-energy physics communities, for example the most recent (June 2002) DOE/NSF Nuclear Science Advisory Committee (NSAC) Long-Range Plan, identifies several research needs that LANSCE's upgrades would satisfy. For example, the NSAC noted that over the next decade expanded research with neutrons is essential to addressing one of the five scientific questions facing the field: What is to be the new Standard Model?

In cold and ultracold neutron research, the NSAC notes the present inability to measure the hadronic weak interaction (cold neutrons) and to test the Standard Model (cold and ultracold neutrons). While the DOE Office of Science, Office of Nuclear Physics, has invested in instrumenting one beamline at the Spallation Neutron Source (SNS) to provide a cold neutron beam for many important nuclear physics experiments of this type, the difference between beam parameters at SNS, and those envisioned at LANSCE, will favor one facility over the other depending upon the experiment. There is no foreseeable redundancy in the UCN facility proposed for LANSCE.

In nuclear astrophysics research, the NSAC emphasizes the need for precision neutron capture cross-section measurements to understand the role of the slow neutron-capture process (s-process) in nucleosynthesis. LANSCE is currently the most advanced facility producing precision neutron capture cross-section measurements; the enhancements proposed here will significantly increase the productivity of this fundamental and critical research.

In accelerator-based neutrino research, two major documents from the high-energy research community provide guidance for future direction. The document "High-Energy Physics Facilities Recommended for the DOE Office of Science Twenty-Year Roadmap" calls for a "high-intensity neutrino super beam, produced by a proton beam with a beam power of a megawatt or more." The American Physical Society (APS) Joint Study on the Future of Neutrino Physics also recommends the construction of such a facility. Such a beam will be available at LANSCE with enhancements. Upgrading LANSCE will require the incremental cost of a target station and detector. Internationally, the Japanese Proton Accelerator Research Project (JPARC) facility will be available, but access will be difficult—if not prohibitive—and overseas project costs for U.S. researchers are greater.

## REQUIREMENTS

### Fundamental Nuclear Physics with Cold Neutron Beams

The subject areas of fundamental nuclear physics are the particles and forces that make up the universe at the simplest level. Experiments with neutrons can provide insight into the behavior of the known types of particles (hadrons and leptons) under all known forces (strong and electroweak) except gravity. As such, neutron experiments provide an unsurpassed opportunity for studying known phenomena and searching for new ones.

Three classes of cold neutron beam experiments in fundamental physics are: 1) precision measurements of neutron decay, including both correlation parameters and the neutron lifetime 2) measurements of the hadronic weak interaction, and 3) a search for a permanent neutron electric dipole moment. The physics reach of these experiments includes: the nature of electroweak theory and the origin of parity violation, a description of the low energy weak interactions between quarks in a strongly bound system, the origin of matter-antimatter asymmetry and time reversal violation; and possible discovery of physics beyond the Standard Model.

LANSCE is a world leader in cold neutron nuclear physics; the staff is expert and experienced in design and construction of this class of experiment. LANSCE leads research efforts in:

- ***Cold Neutron Beam Experiments: Neutron Beta Decay and Hadronic Weak Interaction***
  Neutron beta decay parameters, which are measured from the angular correlation of the detectable neutron decay products (proton, electron) with respect to the neutron spin, and from their energy spectrum, provide a test of the Standard Model of electroweak interactions. For example, precision measurements of these quantities are used to constrain the number of families of fundamental particles to three, and to place limits on the possibility of right-handed currents in the weak interaction.
- ***UCN Experiments Requiring a Cold Neutron Beam: Neutron Lifetime and Neutron Electric Dipole Moment***
  UCNs are trapped magnetically or materially, allowing experiments such as a precision measurement of the neutron lifetime, or a search for the neutron electric dipole moment.

  Trapped UCN decays can be observed and counted to measure the neutron lifetime. Accurate knowledge of the neutron lifetime is necessary for both understanding of Big Bang nucleosynthesis and, when combined with the neutron beta decay asymmetry A, for extraction of the Cabibo-Kobayashi-Maskawa (CKM) matrix element *Vud*; a fundamental parameter of the Standard Model. The neutron lifetime is reasonably well known, but a measurement at the $10^{-5}$ level could provide evidence for new physics.

  Trapped UCNs can also be used to search for a permanent electric dipole moment of the neutron. The neutron has no net electric charge, but an electric dipole moment (EDM) of the neutron would be an example of time reversal symmetry violation. This is related to the matter-antimatter asymmetry of the universe. Current experimental limits on the neutron EDM do not rule out observation of a large ($10^{-26}$ e-cm) neutron EDM, which would be evidence for physics beyond the Standard Model.

*LANSCE is a world leader in neutron nuclear physics and the staff at LANL is expert and experienced in design and construction of this class of experiment.*

### Fundamental Nuclear Physics with Ultracold Neutrons

The Ultracold Neutron Alliance (UCNA) collaboration, using technology developed at LANSCE, has designed and built an ultracold neutron source. The LANSCE-UCN source will provide a dedicated source of UCNs for the UCNA experiment and possibly one or two others using the test beam port. This source will provide more UCNs than any other in the world; densities of hundreds of UCN/cc. This facility will have unique capabilities to study fundamental nuclear physics and probe for new physics, and will support experiments that push the boundaries of the fundamental physics of the weak nuclear force.

Using a 4 microamp proton beam, the source at LANSCE is expected to produce densities of greater than 100 UCN/cc when it starts operating in 2005. An order-of-magnitude greater density of UCN could be achieved in a dedicated user facility, providing many important and unique opportunities for advances in nuclear physics.

*The LANSCE UCN source will provide more ultracold neutrons than any other in the world.*

### Neutrino Physics

Neutrino physics is currently one of the most active areas in elementary particle physics. That the mass values of these smallest of all elementary particles has such a large and dramatic effect on the beginning of the universe, the eventual fate of the universe, and even how much energy is being produced by the sun, and perhaps by the core of the earth, are some of the ironies in nature.

Neutrino physics blossomed in the last decade with the discoveries of neutrino oscillations in several crucial measurements. Since the role of neutrinos in cosmology, supernovas, solar physics, and elementary particle physics have become central to understanding many deep scientific questions, it is apparent that a leading neutrino production facility could play a major role in the next decade, and serve to attract top quality researchers to LANL.

*Since the role of neutrinos in cosmology, supernovas, solar earth physics, and elementary particle physics have become central to understanding many deep scientific questions, it is apparent that a leading-edge neutrino production facility could play a major role in the next decade, and serve to attract high quality researchers to LANL*

## Nuclear Astrophysics

About fifty percent of the element abundances of atomic number greater than iron are produced via the s-process. Starting at the iron-peak seed, the s-process mass flow follows the neutron rich side of the valley of stability. If different reaction rates are comparable, the s-process path branches and the branching ratio reflects the physical conditions in the interior of the star. Such nuclei are important because they provide the tools to effectively constrain modern models of the stars where the nucleosynthesis occurs.

A strong program in nuclear astrophysics fits in well with DOE national nuclear physics program. Research in nuclear astrophysics is emphasized and encouraged by the Nuclear Science Long Range Plan, and is one of the primary motivations for the Rare Isotope Accelerator project *(Appendix E: The Rare Isotope Accelerator {RIA})*. The quest for the origin of the elements is one of "The eleven questions" of science for the new century posed by the National Academies National Research Council.[1] Nuclear astrophysics research provides experimental capabilities and an improved knowledge of hydrodynamics codes, which are vital for developing a science-based predictive capability for nuclear weapons.

*The quest for the origin of the elements is one of "The eleven questions" of science for the new century posed by the National Academies National Research Council.*

*Nuclear astrophysics research provides experimental capabilities and an improved knowledge of hydrodynamics codes, which are vital for developing science-based predictions of nuclear weapons.*

## ENHANCEMENTS MEET THE REQUIREMENTS

The benefits to fundamental nuclear physics research from accelerator upgrades are shown in Figure 1. Note that each of the proposed upgrades maximizes the benefits to one or more areas simultaneously: LANSCE enhancements provide "maximum improved capability" in all four areas; present LANSCE capabilities meet the missions in two areas.

## Cold Neutrons

The number of neutrons available to an experiment essentially scales with the power provided to the spallation target, and with the size and reflectivity of the neutron guide transmitting the cold neutrons to the experimental apparatus.

Regular full 800 MeV capabilities at LANSCE will increase the number of cold neutrons available per hour of delivered beam. Minimal investment in experimental equipment (less than $1M per experiment) will allow both technique development and hadronic weak interaction experiments.

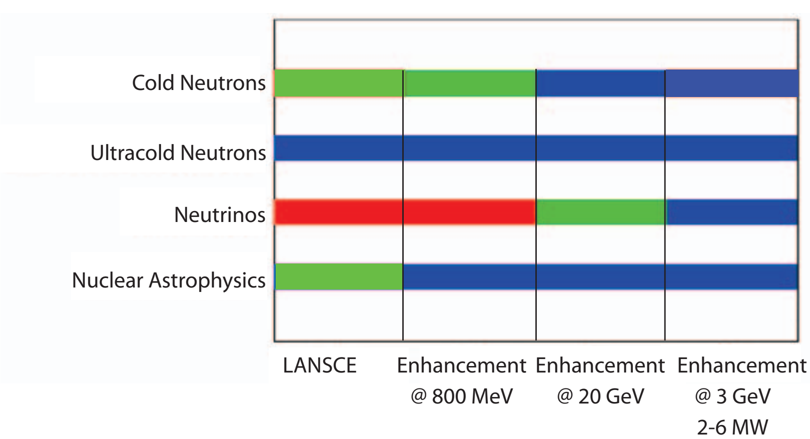
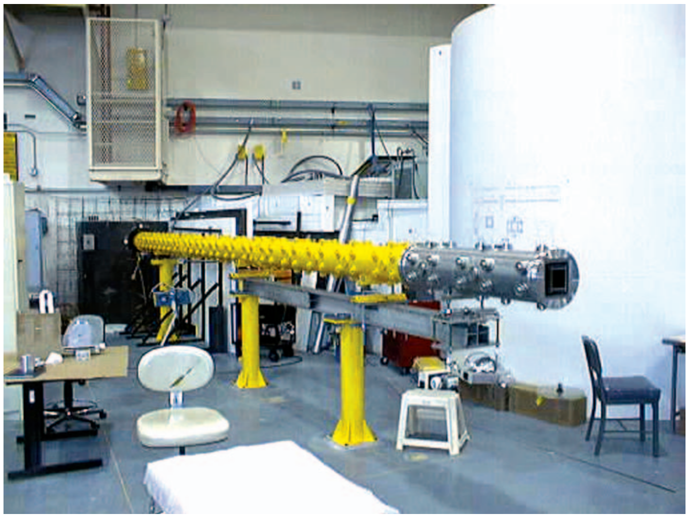



**Figure 1.** This chart shows the degree to which new capabilities are enabled in the four areas of fundamental physics by LANSCE enhancements. Red indicates no capability, **green** indicates some capability, and blue indicates full realization of improved capability.

[1]Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, Committee on the Physics of the Universe, National Research Council, The National Academies Press, 2003.



**Lujan Center's cold neutron beamline provides an intense, pulsed cold neutron source for fundamental nuclear physics research. Neutrons are transported to experiments along this neutron guide. Installation of the neutron guide was completed in Feburary 2003.**

Enhancements at 800 MeV will allow cutting-edge cold neutron beam experiments. The NxGens target station and moderator suite would utilize one third of the 800 MeV, 60 Hz, 2 MW beam (20 Hz, 660 kW). A large "supermirror cold neutron beamline" would provide mission required measurements in future experiments.

Enhancement with a GeV LINAC beam will improve capabilities by a factor of four to ten times depending on enhancement. An enhancement of ten times the current cold neutron flux production of LANSCE will permit experiments to quickly gather statistically powerful data, and to use beam time to perform studies for systematic effects.

LANSCE enhancements significantly improve the:

· Generation of robust event statistics,

· Ability to precisely measure smaller quantities,

· Control over systematic errors, and the

· Ability to demonstrate the absence of false effects (which may mimic the experimental signal of interest).

*An enhancement of ten times the current cold neutron flux production of LANSCE will permit experiments to quickly gather statistically powerful data, and to use beam time to perform studies for systematic effects.*

## Ultracold Neutrons

The production rate from a UCN source of the type installed at LANSCE basically depends on the amount of proton power the accelerator can deliver onto the spallation target in a time comparable to the lifetime of UCNs in the converter volume. At present, the LANSCE-UCN source produces UCNs with a lifetime of about 150 ms, so the more power the accelerator can supply in this time, the higher UCN flux and density can be achieved. Higher instantaneous proton current, higher duty factor, higher energy, or a combination of all three will supply the additional proton power to the spallation target. For example, the beam from a 3 GeV LANSCE enhancement will, when incident on the spallation target of the LANSCE-UCN source, produce about three times as many UCNs.

Increasing the UCN production from a solid deuterium-based source, such as the one at LANSCE, will improve the conversion efficiency from spallation neutrons to ultracold temperatures, and improve the efficiency of extracting UCNs from the converter material and delivering them to experiments. A source based on a solid oxygen converter, for example, instead of a solid deuterium converter, is predicted to produce about fifty times greater UCN flux and density. The production rate is approximately the same between the two materials, but the efficiency with which UCNs can be extracted from a solid oxygen converter is thought to be many times higher than is possible with solid deuterium.

Improvements to the UCN extraction from the source will allow the same UCN source to supply neutrons to multiple experiments simultaneously, instead of just one at a time, as the dedicated source at LANSCE does. By extracting the neutrons at speeds above the UCN cutoff speed of about 8 m/s, then slowing them down to UCN speed by reflecting them from receding turbine blades, multiple UCN beamlines can be served with the same UCN flux and density that simple extraction of UCNs can supply to a single beamline. With multiple beamlines driven at full intensity, multiple users could field experiments simultaneously. Considering the infrastructure already in place to support the existing UCN source, LANSCE is the natural choice of where to build a high-intensity user facility. The enhancement would support a user group of about 150 scientists, with several experiments accepting UCNs, at any time with several more preparing to take beam.

Enabled with a high-intensity UCN source, the facility will support new classes of experiments—neutron EDM measurements, neutron lifetime measurements, measurement of further properties of neutron beta decay (e.g. the correlations between the other decay particles), measurement of neutron-antineutron oscillations, and neutron-neutron scattering measurements.

By increasing available UCN densities, UCN measurements that previously would have been impossible—become reality.

*By increasing available UCN densities, UCN measurements that previously would have been impossible—become reality.*

## Neutrino Physics

Enhancement options provide for energy in the range of 3 GeV to 20 GeV to inject into a proton radiography machine allowing advanced experimentation for weapons research.

A high-energy pRad ring provides the opportunity to build in the same tunnel, an inexpensive compression ring, made out of permanent magnets. The large circumference of the pRad ring will accommodate the lower field permanent magnet ring. The low-cost permanent magnet ring could be designed to accommodate energy in the range of 2 to 3 GeV. Initially the facility could operate as a stopped-muon source, with expectation that a decay-in-flight beam line will be constructed. These upgrades will greatly enhance the measurements of neutrino oscillations.

The ultimate precision in neutrino oscillation physics requires an advance in accelerator technology; the development of a cooled-muon storage ring. The muons are produced via the same pion decays that produce muon neutrinos, but then diverted into a cooling channel to reduce their phase space sufficiently to be inserted into a storage ring. Once in the ring, the muons decay in the straight sections of the storage ring to produce a tightly collimated beam of neutrinos of very high brightness. The muon storage ring is expected to provide the most precise measurements of neutrino oscillations. There is currently a growing R&D effort in the area of muon storage rings, whose first application will be a neutrino factory. Next, it could be used to construct a large and significantly improved muon colliding beam facility, placing LANSCE at the forefront of high-energy physics.

It is important to note the possibility of light-sterile neutrinos, CPT violation, and mass-varying neutrinos physics. LANSCE's upgrades could provide significant opportunities to observe new physics. This is a field where there is little experimental data, but much theoretical direction. Neutrino physics research may prove to be a revolutionary scientific direction, pointing the way beyond the Standard Model.

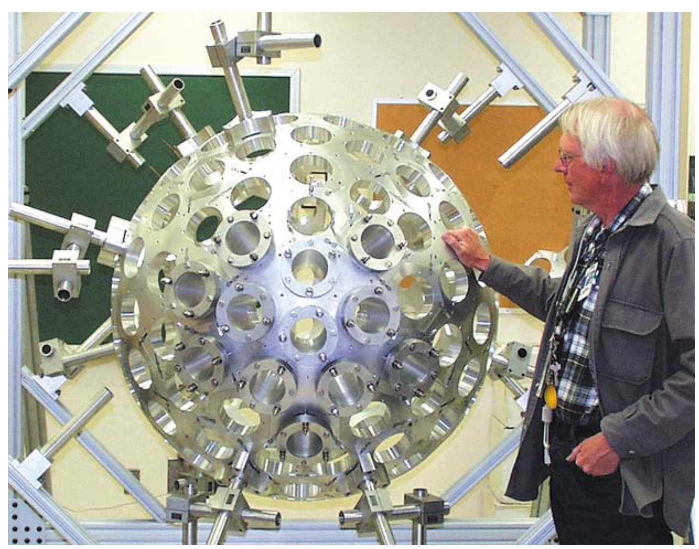
*Neutrino physics research may prove to be a revolutionary scientific direction, pointing the way beyond the Standard Model.*

## Nuclear Astrophysics

The radioactivity of a given isotope is inversely proportional to the sample mass available for experimentation. This means that measurements on short half-life isotopes require very low mass samples and concomitantly, a high neutron flux.

The Lujan Center at LANSCE is presently the center-of-excellence for investigating neutron capture reactions. Although it was never optimized for neutron experiments in the keV region, it is currently the most powerful facility in the world. LANSCE upgrades will significantly enhance neutron flux in the keV region by a factor of ten to 100. Some of the optimization elements are:

- Increasing the number of protons per pulse from the proton storage ring.
- Designing a new moderator-target at WNR, where the flight path views a thin moderator, which is directly in front of the neutron production target.
- Using the PSR to stack single micropulses and drive the moderator-target at WNR.[1]
- Moving the DANCE instrument to WNR to take advantage of these neutron flux improvements.



**The Detector for Advanced Neuton Capture Experiments (DANCE) studies neutron capture reactions of radioactive or rare stable nuclei on small quantities: on the order of 1 mg. These reactions are important for research in weapons physics, radiochemistry, and element formation in stars.**

[1]IEEE Transactions on Nuclear Science, Vol. NS-32, p. 2662, 1985.

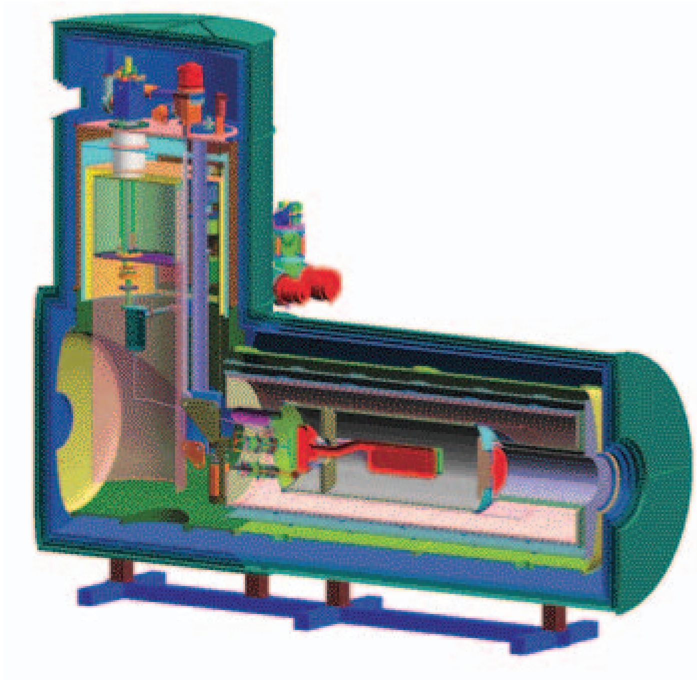


**Figure 2.** Conceptual drawing of the neutron electric dipole moment experiment currently being developed at LANL. The apparatus is approximately 5.6 m tall.

Neutron capture cross-sections of isotopes with half-lives down to a few days can be investigated with these improvements.

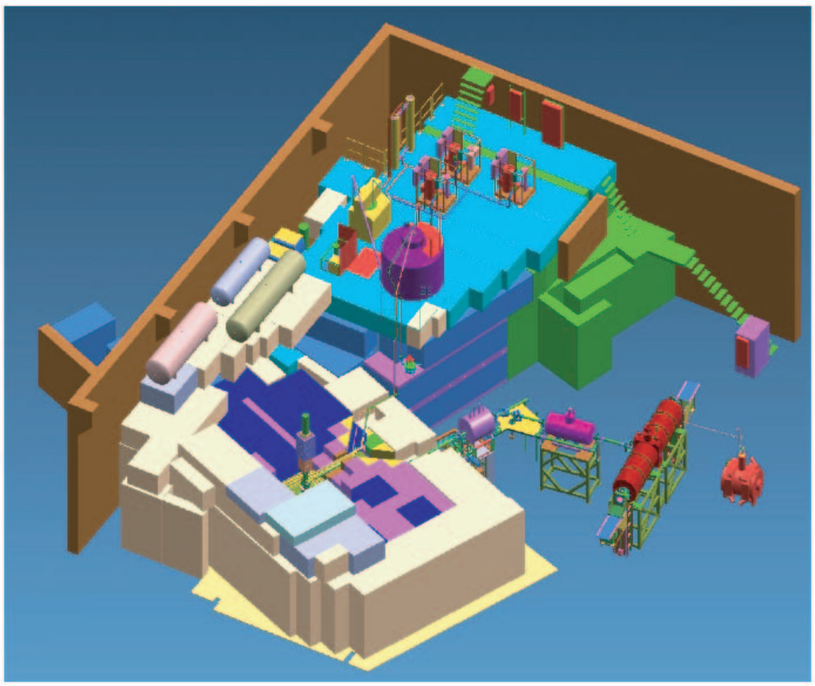
*The Lujan Center at LANSCE is the center-of-excellence for investigating neutron capture reactions.*

## SUMMARY

To meet national missions, LANL recognizes and emphasizes the need for strong research in fundamental nuclear physics—research that is also critical to supporting LANL's wider programmatic efforts.

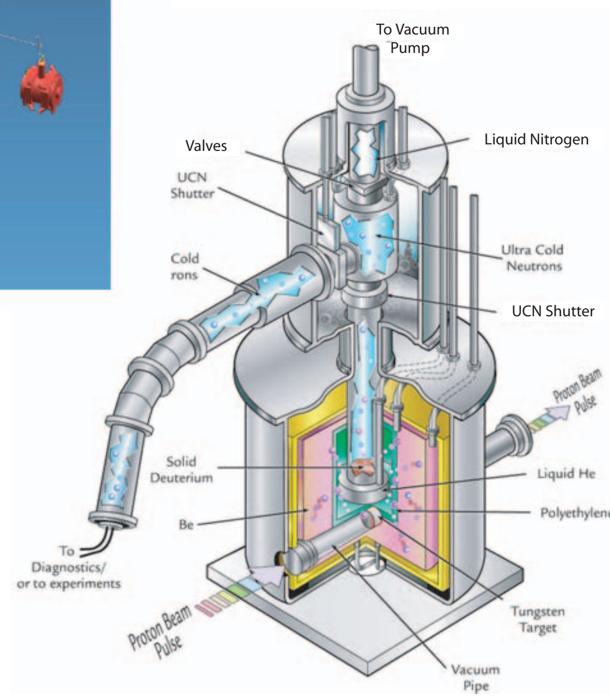
LANSCE enhancements provide LANL the ability to evolve with, and catalyze further evolution in, fundamental nuclear physics research and applied nuclear physics *(Appendix F: LANSCE-E Provides Additional Capabilities and Opportunities in Nuclear Science with Antiprotons)*. LANSCE will continue to be a magnet for scientific research excellence and productivity, and to meet national security and defense missions.

*The Lujan Neutron Scattering Center, with the DANCE detector and with WNR, is currently the most powerful experimental setup for neutron capture measurements in the keV region in the world.*



Ultracold Neutron Layout

**The ultracold neutrons are generated by down-scattering spallation neutrons from liquid helium after moderation in solid deuterium. This technique allows systematic effects to be much smaller than with similar neutrons at other reactors. LANSCE's UCN production experiment achieved a world record in UCN density—calculations predict several hundred UCN/cc. The first experiment will be a precision polarized neutron-β-decay measurement.**




The Ultracold Neutron Source

## WORKSHOP ON THE FUTURE OF NUCLEAR PHYSICS AT LANSCE

### July 28 and 29, 2005
### Los Alamos National Laboratory

*It is clear that a refurbished LANSCE would continue to be a world-class facility for research in nuclear astrophysics, nuclear structure physics, and cold neutron physics. Furthermore, enhancements to LANSCE could place it at the forefront for experiments employing neutron beams in these fields, as well as making possible a complimentary program in the production of radioactive samples for research in these, and other areas. In addition, it is expected that these refurbishments and/or enhancements to LANSCE would continue, and perhaps even strengthen, ties between basic and programmatic research at Los Alamos National Laboratory.*

### Nuclear Astrophysics

The combination of high neutron flux at the Lujan Center and high efficiency and high granularity of the DANCE detector have made possible detailed neutron capture measurements on microgram-sized radioactive samples. As a result, astrophysical neutron-capture reaction rates for radionuclides can be determined across a range of temperatures needed to test and improve astrophysical models. For example, there are many radionuclides in the path of the nucleosynthesis flow during the slow-neutron-capture process, or s-process. The competition between neutron capture and beta decay causes the nucleosynthesis flow to branch at these nuclides; hence, "branching points." If the reaction rates for these branching points can be determined, then this competition can be used to constrain the neutron density, temperature, and matter density during the s-process, providing stringent tests for s-process models. However, there have been very few reaction-rate measurements on these branching points, because previous techniques required samples that were so large they were too expensive to produce, and/or too radioactive to use in experiments. The first few measurements on radioactive samples at DANCE have begun to show the promise of the facility.

As exciting as the prospect of this new capability is, the amount of sample needed still limits measurements to nuclides with half-lives longer than about one year. In addition, the relatively poor resolution, together with the moderate flux at the Lujan Center above approximately 10 keV, limits the accuracy to which these rates can be determined.

Upgrades to LANSCE to increase the flux and improve the resolution, in the keV to few hundred keV energy range, would greatly expand the number of radioactive samples on which accurate reaction-rate measurements could be made.

*The complete report from this workshop is in press.

This combination of high flux and excellent resolution would surpass that at any other facility in the world. It would make reaction rate measurements on almost all isotopes of interest to the s-process feasible—and would place LANSCE at the forefront of neutron nuclear astrophysics research. Moreover, it appears only relatively modest enhancements to the current LANSCE facility would be needed to achieve these aims.

### Nuclear Structure Physics

These same enhancements could greatly increase the number and quality of experiments in nuclear structure physics. The advent of sophisticated new detectors, such as DANCE, GENIE, and FIGARO, has provided a wealth of new information to test and improve nuclear structure models. However, many of the experiments are very time consuming, and the range of nuclides that can be studied, as well as the detail of the information obtainable from the data, are limited by the current flux and/or resolution. For example, recent experiments have revealed strong enhancements in the low-energy $\gamma$-ray strength functions in several nuclides. The observed enhancements were unexpected and currently are unexplained by any model. The multitude of information about $\gamma$-ray cascades following neutron capture reactions obtainable with the DANCE detector should make it possible to study this enhancement with unprecedented detail. However, currently it is possible to make detailed measurement only for strong resonances at low energies using relatively large samples. Enhanced flux and resolution would make it possible to expand this work to a wider range of nuclides and resonances.

These enhancements to LANSCE would also facilitate a wide variety of other interesting nuclear structure experiments that, currently, are limited by flux and/or resolution—such as the study of quantum chaos, a better understanding of the fission process, and searches for signatures of three-body forces.

Finally, the physics case for a Radioactive Ion Beam (RIB) facility is well documented, and construction of such a facility is a high priority within the DOE. The advent of the Materials Test Station (MTS) at LANSCE presents the possibility of developing a RIB facility, complementary both to other programs at LANSCE and to other proposed and operating RIB facilities. By placing a uranium target and RIB extraction mechanism in the high neutron flux of the MTS, it should be possible to produce copious amounts of radionuclides. The addition of an isotope separator and/or target implantation device would make it possible to produce radioactive samples for use at DANCE or the Lead Slowing Down Spectrometer at the Weapons Neutron Research facility, or facilities outside Los Alamos. Current facilities for producing radioactive samples are very limited and will probably present a serious bottleneck for future experiments.

**Recommendations**

1) The feasibility of implementing the super-micropulse mode of operating the LANSCE proton storage ring (PSR) should be explored as soon as possible. If these tests are successful, then the first phase of this upgrade should be undertaken. Operation with multiple super-micropulses in the PSR should also be tested. If successful, further upgrades to LANSCE (for example, an extraction kicker to allow multiple pulses to be extracted from the PSR) should be implemented to allow operation in this mode.

2) The feasibility of inserting a RIB production source in the MTS should be studied as soon as possible, and the MTS should be designed in such a way that it does not preclude the insertion of such a source. If a RIB source can be shown to be able to generate sufficient amounts of radionuclides for producing useful samples for subsequent experiments at DANCE, the Lead Slowing Down Spectrometer (LSDS), and/or other facilities, then it should be implemented.

## Cold Neutron Physics

The field of neutron physics has become an integral part of investigations into an array of important issues that span fields as diverse as nuclear and particle physics, fundamental symmetries, astrophysics and cosmology, fundamental constants, gravitation, and the interpretation of quantum mechanics. Some of the experimental endeavors include measurement of neutron-decay parameters, the use of parity violation to isolate the weak interaction between nucleons, and searches for a source of time-reversal violation beyond the Standard Model. These experiments provide information that is complementary to that available from existing accelerator-based nuclear physics facilities and high-energy accelerators. Neutron physics measurements also address questions in astrophysics and cosmology. The theory of Big Bang nucleosynthesis needs the neutron lifetime, and the vector and axial vector weak couplings, as input, and neutron cross sections on unstable nuclei are necessary for a quantitative understanding of element creation in the universe.

The expanding scientific opportunities in fundamental neutron physics are attracting a growing number of young researchers. This growth is driving the increasing number and variety of new facilities.

The development of a next generation, high flux, long pulse spallation source (NxGens) would benefit the following areas of research:

***Neutron Decay Parameters***

Neutron decay is an important process for the investigation of the Standard Model of electroweak interactions. As the prototypical beta decay, it is sensitive to certain Standard Model extensions in the charged-current electroweak sector. Increasingly precise measurements of the neutron lifetime, and the decay correlation coefficients, are possible with NxGens technology.

***Neutron-Nucleon Weak Interactions***

The most obvious consequence of the weak interaction for neutrons is that it makes neutrons unstable. In addition to the coupling of quarks to leptons that allows decay, electroweak theory also predicts (and experiments confirm) that there are weak interactions between the quarks in the neutron with couplings comparable in size to those involved in neutron decay. The weak nucleon-nucleon interaction is a unique probe of strongly interacting systems. There is clearly a need for experiments to better understand these interactions. Studies with cold neutrons offer the best promise for significant improvements in knowledge.

***Low Energy Quantum Chromodynamic (QCD) Tests***

One of the long-term goals of strong interaction physics is to see how the properties of nucleons and nuclei follow from QCD. The ultimate goal is to illuminate the strongly interacting ground state of QCD, the most poorly understood sector of the Standard Model.

***Nonstandard T- and B-Violation Searches***

The physical origins of the observed charge conjunction and parity violation (CPV) in nature, first seen in the neutral kaon system, remain obscure. This CPV implies time-reversal symmetry (T) violation (and vice versa), through the CPT theorem. The Standard Model can accommodate the possibility of CPV, through a complex phase in the the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. To date, there is no firm evidence against the possibility that the observed CPV effects are due to this phase, but the question remains whether or not there are sources of CPV other than, or in addition to, CKM matrix.

Antimatter appears to be rare in the universe, and there is an asymmetry between the number of baryons and antibaryons. Although the Standard Model possesses a mechanism to violate baryon number, no experiments have seen B-violation. Some physics beyond the Standard Model must exist if the observed baryon asymmetry is to be understood.

One of the key experiments that could probe this area is a search for neutron-antineutron oscillations. Although there has been some discussion of possible strategies to improve on the bounds from direct searches using cold and ultracold neutrons, there are no new free neutron-antineutron oscillation searches underway. This remains an outstanding challenge for the neutron physics community.

## Ultracold Neutron Research

In the last five years, the superthermal source concept has stimulated tremendous growth in the field of ultracold neutron research. Ultracold neutrons (UCN) are neutrons with velocities below about 9 m/s. Neutrons with these low velocities can be stored in material bottles for hundreds of seconds, and provide an ideal tool to study a number of the fundamental properties of the neutron. For example, at present, ultracold neutron experiments provide the definitive limit for the static electric dipole moment (EDM) of the neutron, and the most precise measurements of the lifetime of the neutron. Progress on other measurements using UCN, such as measurements of decay angular correlations, neutron-antineutron oscillations, and studies of solid state dynamics, have been hampered by the low available fluxes of UCN. Typically, only a few UCN/cm$^3$ are made available even at the most intense UCN source—the Institut Laue-Langevin in Grenoble.

A UCN beam line will be implemented at the SNS. However, it will be based on superthermal UCN production in liquid helium, and will be devoted exclusively to studies of the neutron EDM, and the neutron lifetime. The recent implementation at LANSCE of superthermal sources, with potentially much greater UCN densities, is based on a solid deuterium superthermal source coupled to a 3.2 kW spallation target. World record UCN densities of 145±7 UCN/cm$^3$ were produced by a prototype for this source in 2000. Such intensities are spurring a wave of novel UCN nuclear physics experiments and attracting new experimental groups to the field, and the exploration of new source options, such as a solid oxygen UCN converter material, can potentially have a very large impact on the field.

The initial focus of the LANSCE source is, for the first time, to utilize UCN for angular correlation measurements in neutron beta-decay. Although optimized for measurement of decay betas, the experiment can also be modified to detect the recoil protons following beta-decay. This should permit measurements of the proton-asymmetry, and measurements of the electron-neutrino correlation. A preliminary assessment of these experiments indicates that statistical precisions at, or below, the 0.1 percent level should be achievable with the planned LANSCE source. These measurements provide alternate methods to determine the $V_{ud}$ element of the CKM (quark mixing) matrix, and complementary constraints on the Standard Model to those provided by the beta-asymmetry. In addition, the spectrometer can be used to perform high-precision beta-spectroscopy of neutron decay, leading to possible constraints on the Fierz interference term, recoil order terms (weak magnetism and induced tensor form factors), and various extensions to the Standard Model. Angular correlations experiments are also possible at LANSCE's UCN source to determine the time-reversal non-invariant angular correlation proportional to the D-coefficient.

Any program to determine the charged current parameters in neutron decay must also include a measurement of the neutron lifetime. Such a measurement, using a magnetic bottle coupled to the "test" beam line at LANSCE's UCN source, is already under development. With modest UCN densities, such an apparatus can provide limits at, or below, the one second precision level, and therefore improve our current determination of the neutron lifetime. These measurements contribute to the establishment of the CKM element $V_{ud}$ and provide constraints on Big Bang nucleosynthesis models.

Ultracold neutrons provide a unique tool for probing very simple quantum-mechanical systems. For example, the quantization of UCN wave functions in a gravitational field have been observed, and high-precision spectroscopy of these gravitational levels may lead to various tests of our understanding of the gravitational interaction at short distance scales.

The UCN storage in material bottles provides the opportunity to explore a variety of exotic interactions with the surface, including extremely small energy exchange (at the level of neV) with surface layers, and the possibility of Anderson localization. There is already an active program in the U.S. (and abroad) to utilize the inelastic interaction of UCN with surfaces to explore the solid state dynamics of surface layers and membranes. These research programs will immediately benefit from the higher UCN densities projected for the LANSCE-UCN source. The UCNs also experience extraordinarily enhanced nuclear absorption cross-sections because of the typical 1/v dependence of these cross-sections, which may lead to useful information concerning absorption processes.

An intense UCN source may also be used to place limits on neutron-antineutron oscillation. These measurements provide unique constraints on baryon number violating interactions, which shed light on the origin of the cosmological baryon-antibaryon asymmetry, and the origin of neutrino mass. To be competitive with underground measurements, the program requires more UCN intensity than available with the initial implementation of the LANSCE source. Increases in current, optimization of UCN delivery, and exploration of new converter materials (such as solid oxygen) may result in the necessary UCN densities for these measurements. At present, research and development for these experiments is possible, and may serve to determine the ultimate sensitivity of these measurements.

**Recommendation**

UCN's can have applications in research areas ranging from fundamental particle and nuclear physics, to materials physics and biological physics. An upgraded LANSCE facility with a general purpose beam line optimized for UCN production in solid deuterium and/or oxygen will attract a broad group of users. Complementing capabilities at the SNS, the facility will allow measurements of neutron beta decay correlations to unprecedented precision, could open up new ways of studying surfaces and membranes, and could lead to the first study, in decades, of neutron-antineutron oscillations.

## Future Neutrino Initiatives

The American Physical Society's Joint Study on the Futures of Neutrino Physics (2004) recommended, as one of its three top-level recommendations, the following:

*"A proton driver, in the megawatt class or above, and neutrino superbeam with an appropriate, very large detector capable of observing charge conjunction and parity violation, and measuring the neutrino mass-squared differences and mixing parameters with high precision."**

Upgrades to the LANSCE facility, combined with an intense proton driver and neutrino source, can provide the beam necessary to carry out the APS's recommendations. We reviewed two options:

***1) Long Baseline, Off-axis Neutrino Oscillation Physics***
For the three standard model neutrinos, there is still one mixing angle to measure. If this angle is large enough, there is also the possibility of looking for a charge conjunction and parity violating phase. Long baseline neutrino oscillation physics programs can probe these, plus the mass hierarchy in the neutrino sector. But, to do so requires intense neutrino beams, massive detectors, and very long baselines. The wide-band program requires proton energies ~ 20 GeV, while the off-axis programs typically require higher energies. Upgrades to LANSCE could produce these requirements.

There are plans to build a very massive detector near Soudan, Minnesota, for an off-axis program at Fermilab, using the existing NuMI neutrino beam. A program using a neutrino beam from LANSCE, coupled with a massive detector at Soudan, would be a very sensitive tool in the search for a charge conjunction and parity violation in the neutrino sector.

***2) Medium Baseline, Neutrino Oscillation Physics Using 3 GeV***
Another option is to utilize a rapid-cycling synchrotron or superconducting LINAC to produce a medium energy neutrino beam with a mean neutrino energy of ~ 350 MeV. Such a facility, for the same ratio of detector distance to neutrino energy (L/E) and beam power, would provide approximately the same neutrino event rate as from a 20 GeV proton source and provide a similar physics program of $\theta_{13}$, $\delta$, and mass hierarchy measurements. A 3 GeV rapid-cycling synchrotron, however, would have a much lower $\nu_e$-background, due to the suppression of kaon production in the primary proton interactions and the reduced rate of neutral-current $\pi^\circ$ neutrino events. The suppression of kaon production would lead to a lower intrinsic $\nu_e$-background, while the reduced rate of neutral-current $\pi^\circ$ events would lead to a lower $\nu_e$ misidentification background. With the lower intrinsic $\nu_e$ and $\nu_e$ misidentification backgrounds, an experiment at the
3 GeV facility should be sensitive to lower values of $\theta_{13}$ and should have lower measurement uncertainties. In addition, the event topologies at a 3 GeV facility will be simpler than for a 20 GeV facility, thereby facilitating the use of inexpensive liquid-Cherenkov detectors.

For the same L/E, the neutrino travel distance will be proportionately smaller for the 3 GeV facility than for the 20 GeV facility. The shorter distance creates the possibility of using the Henderson Mine, the Homestake Gold Mine, or the Waste Isolation Pilot Plant for the detector location. An additional advantage is that the angle of the neutrino beam line below the surface would be less, making excavation and tunneling easier, and allowing the construction of near detectors for the determination of the neutrino flux and cross-section. Clearly, the use of a 3 GeV rapid-cycling synchrotron for long base line neutrino oscillation physics is advantageous.

***Neutrino Scattering Physics***
With the possibility for new intense neutrino sources there is a re-kindled interest in conventional neutrino scattering physics measurements. Measurements that probe nucleon structure have suffered in the past from large statistical and systematic errors. New, well-understood intense neutrino beams, coupled with fine-grained detectors, can perform these precision neutrino scattering physics measurements. In particular, neutrino-proton elastic scattering can probe the spin carried by the strange quarks in the nucleon, $\Delta s$. Neutrino scattering provides the only robust way to measure the strange part of the axial form factor, and extrapolate it downwards. Folding in antineutrino-proton elastic scattering provides a tool for correcting systematic errors. With fine-grained detectors and intense neutrino beams, $\Delta s$ can be measured almost an order-of-magnitude better than existing measurements.

***Beta Beams***
Another long-term possibility for doing neutrino oscillation physics involves use of a new kind of neutrino source: beta beams. Beta beams of radioactive elements are accelerated to high energies, and allowed to decay in "racetrack" machines, into neutrinos (and other decay products). The neutrino spectrum produced by these beams is monoenergetic (by comparison to neutrinos from

*The Neutrino Matrix: DNP/DPF/DAP/DPB Joint Study on the Futures of Neutrino Physics, prepared by the members of the American Physical Society Multi-Divisional Neutrino Study, p. 28, November 2004. http://arxiv.org/abs/physics/0411216.

conventional sources), and thus a huge asset for energy-dependent neutrino-oscillation physics measurements. Neutrino scattering physics, using beta beams, is also of interest; low-energy, mono-energetic neutrinos are ideal for measuring cross sections necessary to understand neutrino interactions in supernovae. A beta beam capability at LANSCE, combined with a new intense, high-energy accelerator, would be a superior facility to what CERN currently envisions.

**Participants**

Undraa Agvaanluvsan, Lawrence Livermore National Laboratory
David Bowman, Los Alamos National Laboratory
Tim Black, University of North Carolina, Wilmington
Todd Bredeweg, Los Alamos National Laboratory
Carla Breiner, Los Alamos National Laboratory
Tom Bowles, Los Alamos National Laboratory
Joe Carlson, Los Alamos National Laboratory
Linda Coney, Columbia University
Martin Cooper, Los Alamos National Laboratory
Adrian Fabich, CERN
Brad Filippone, California Institute of Technology
Bonnie Fleming, Yale University
Chris Gould (co-chair), North Carolina State University
Joseph Ginocchio, Los Alamos National Laboratory
Bob Haight, Los Alamos National Laboratory
Ken Hanson, Los Alamos National Laboratory
Ernest Henley, University of Washington
Peter Herczeg, Los Alamos National Laboratory
Paul Kochler, Oak Ridge National Laboratory
Toshihiko Kawano, Los Alamos National Laboratory
Tom Kirk, Brookhaven National Laboratory
Paul Lisowski, Los Alamos National Laboratory
Gail McLaughlin, North Carolina State University
Andre Michaudon, Los Alamos National Laboratory
Jeff Nico, National Institute of Standards and Technology
Philip Page, Los Alamos National Laboratory
Michael Ramsey-Musolf, California Institute of Technology
Rene Reifarth, Los Alamos National Laboratory
Alex Saunders, Los Alamos National Laboratory
Richard Schirato, Los Alamos National Laboratory
Kurt Schoenberg, Los Alamos National Laboratory
Albert Steyerl, University of Rhode Island
Walter Sondheim, Los Alamos National Laboratory
Richard Sheffield, Los Alamos National Laboratory
Rex Tayloe, Indiana University
Robert Tribble, Texas A&M University
Dave Vieira, Los Alamos National Laboratory
Steve Wender, Los Alamos National Laboratory
W. Scott Wilburn (co-chair), Los Alamos National Laboratory
Jan Wouters, Los Alamos National Laboratory

*Authors:*
*Bonnie Fleming, Yale University*
*Paul Koehler, Oak Ridge National Laboratory*
*Jeff Nico, National Institute of Standards and Technology*
*Albert Young, North Carolina State University*

# Appendix

Chapter 2
87 Appendix A: Strategic Areas *of* Neutron Scattering Research
95 Appendix B: LANSCE's Current Capabilities
97 Appendix C: Comparative Analysis *of* Present *and* Future Neutron Scattering Facilities

Chapter 3
101 Appendix D: Materials Test Station

Chapter 5
105 Appendix E: The Rare Isotope Accelerator (RIA)
109 Appendix F: Additional Capabilities *and* Opportunities *in* Nuclear Science *with* Antiprotons

G and H
111 Appendix G: LANSCE Accelerator Refurbishment *and* Enhancement Options
123 Appendix H: Abbreviations *and* Acronyms

# Appendix A: Future Strategic Areas of Neutron Scattering Research

## INTRODUCTION

The impact of neutron scattering is evident across all of materials science. Recent examples include: understanding the anomalous thermal expansion in plutonium, elucidation of the physics of high-temperature superconductivity, the discovery of water inclusions in DNA structure, and the identification of material failure modes in high-consequence accidents. The growing power of neutron sources and increasing sophistication of associated instrumentation assure an expanding role for neutrons in materials research, particularly regarding the physical and chemical origins of material properties. A brief summary of neutron scattering research follows.

## SOFT MATTER

### Synopsis

Neutron scattering techniques play a unique role in the study of both the structural and dynamical properties for a wide range of substances categorized as “soft matter.” *Neutron scattering is the only tool for unraveling both the molecular morphology and motions in soft-matter systems across the relevant length scales.* Unlike synchrotron x-rays, neutrons do not produce serious radiation damage in polymeric or biological samples—a powerful advantage. In addition, it is possible to manipulate the contrast, by deuteration, of hydrogenous constituents and thereby sort out the structure of complex systems.

Morphological features can be very large and the dynamics can be very slow. These characteristics of soft matter drive the need for high-intensity, long wavelengths and long pulses. In addition, future trends will require investigations of dilute components as well as minority components concentrated at topologically unique points or at interfaces.

In many cases these experiments involve polarization analysis, short-time measurements and *in situ* studies. A growing need in soft matter is for simultaneous measurements involving laser spectroscopy, light scattering, ultrasound, bi-refringence, dichroism, electronic transport, and photophysics during pulsed-neutron-scattering experiments. Most of these soft-material studies are directly correlated to technological applications with a strong impact in the fields of nanotechnology and functional materials.

***Scientific and Programmatic Opportunities***

- Structure Formation, Self-assembly, Protein Folding and Bio-mineralization
- Self-healing Materials, Environmentally Responsive Materials, Photonic Crystals, Drug Delivery Systems, and Tailored Catalysts Supports
- The Behavior of Complex Fluids in Porous Media
- The Collective Dynamics in Disordered Complex Materials to Understand the Molecular Basis of Rheology, to Solve the Mysteries of the Glass Transition, and to Address the Dynamics of Surfaces
- The Properties of Minority Components Multicomponent Formulations Including Oil Additives, Detergents, Food Additives, Compatibilizers and Cosmetics
- Surface Phase Transitions and Membrane-protein Interactions for Biosensors

***Instrumentation Requirements***

- SANS (Small Angle Neutron Scattering), Including Conventional, Magnetic, Focusing, and Spin-echo for Higher Resolution
- USANS (Ultra Small-angle Neutron Scattering) to Probe Dimensional Scales Approaching 10 mm
- Reflectometers with Neutron Spin-echo
- TOF (Time-of-flight) Cold Neutron and Backscattering Spectrometers

## BIOLOGY AND BIOTECHNOLOGY

### Synopsis

The sequencing of the genomes of human and other organisms has created "...a revolution in biology that has no equal in the history of science. *Our perspective is forever changed*," writes Marvin Fraser.[1] In the post-genomics era focus has partly shifted to the characterization and function of proteins—the product of genes. Several initiatives (e.g. the National Institutes of Health’s National Institute of General Medical Services’ Protein Structure Initiative) seek to

[1]Stepping Up the Pace of Discovery: The Genomes to Life Program, Frazier, M., et al. 2003, 2003 IEEE Bioinformatics Conference. CSB2003, 11-14 Aug. 2003, Stanford, CA, USA; pp. 2-9.

determine protein structures in a high-throughput mode using x-ray crystallography and nuclear magnetic resonance (NMR) spectroscopy. Expected benefits include illuminating structure-function relationships and structure-based drug design, as well as better understanding of biophysical and biomedical problems such as protein folding, evolution, structure prediction, and the organization of protein families.

An even more ambitious goal is DOE's Genomes to Life (GTL) program, which seeks to understand the life processes of thousands of microbes at a molecular level. Achieving a systems understanding of life is "...one of the most daunting challenges in the history of science."[2] The GTL will also provide the scientific foundation for solving urgent problems in energy, global climate change and environmental cleanup.

The biosciences community at LANL is responding to these challenges by strategically consolidating its capabilities in predictive and quantitative biology to solve complex problems regarding health, energy and environmental security.[3] LANSCE supports this vision through a structural biology beamline, the Protein Crystallography Station (PCS), as well as other shared beam lines such as Surface Profile Analysis Reflectometer (SPEAR) and Low-Q Diffractometer (LQD). The PCS is the only resource of its kind in North America—*it is heavily oversubscribed.*

Neutron crystallography is important in post-genomic structural biology because it is the only practical technique for locating hydrogen atoms. Knowing where hydrogen atoms are is important for understanding proteins, especially enzymes. Hydrogen atoms are the primary motive force in most enzymatic reactions. Neutron crystallography provides crucial information on the mechanism of a number of enzymes.

Enhanced LANSCE capability would support two of the LANL bioscience initiatives: science at the interface of public health and national security, and microbial diversity and its application to energy and environmental security. Given LANL's strategic investment in bioscience, the NxGens would provide the institutional resource required to make LANL the premier international center for the application of neutrons to biology.

An immediate impact of a NxGens would be gains of up to two orders-of-magnitude, or more, on existing instruments at LANSCE. Currently only a fraction of protein crystals are large enough for neutron studies owing to limitations in available neutron flux. Some flux gains will be realized at the Spallation Neutron Source at Oak Ridge National Laboratory (SNS) first target station. Far greater gains are possible, however, with the LPSS, so neutron crystallography could become a routine tool for probing the mechanism of newly discovered enzymes, and guiding both drug development and molecular therapeutics.

*Only a fraction of protein crystals are large enough for neutron studies owing to limitations in available neutron flux... potential gains of over two orders-of-magnitude with the NxGens at LANSCE would allow neutron crystallography to become a routine tool for probing the mechanism of newly discovered enzymes, and guiding both drug development and molecular therapeutics.*

Both SPEAR and LQD are flux-limited. A SPEAR-like reflection on a NxGens would be a potentially powerful tool for studying self-organization processes and functional aspects of *native* membranes. Such studies are important for membrane-based biosensors as well as for understanding viral and toxic diseases. The LQD would become a routine tool for studying the interaction of proteins i*n vitro* and *in vivo* within their cellular environment.

A NxGens would also stimulate new experimental techniques in biology. Molecular dynamics our crucial to biological function. NxGens would also provide the flux necessary to carry out spectroscopic measurements of complex biological systems as they execute biological function. An example is drug design, where it is recognized that drug-docking is a dynamic event. Experimental information on protein dynamics would greatly aid modeling of docking dynamics. Dynamic pathways are also important in protein folding, enzyme function, and the biology of membranes.

***Scientific and Programmatic Opportunities***

- Self-organization Processes and Functional Aspects of Native Membranes
- Interaction of Proteins *In Vivo* Within Their Cellular Environment
- Kinetic Studies of Macromolecular Interactions
- Elucidation of Enzyme Mechanism
- Mechanisms of Drug Binding and Drug Delivery
- Drug Design
- Design and Characterization of Membrane-based Biosensors and Biochips
- Viral Assembly
- Biomembrane Physics, Including Toxin Attacks
- Improving Biocompatibility in Medicine
- Understanding Food Processing at the Molecular Level

Deuterium labeling is a superb tool to highlight specific components of complex biosystems. It is also important for

[2] *ibid.*
[3] Los Alamos National Laboratory Bioscience Division White Paper, January 27, 2005.

locating hydrogen atoms and water molecules in neutron-protein crystallography. Research on all the above flagship activities is critically dependent on the availability of deuterium-labeled macromolecules.

***Instrumentation requirements***

- High-resolution Backscattering
- High-resolution and High-intensity Protein Diffractmeters
- Variable Cold-chopper Spectrometers (both High-intensity and High-resolution)
- High-resolution Neutron Spin Echo
- High-intensity Reflectometer
- High-intensity SANS
- 17-μeV Resolution Backscattering Spectrometer
- Molecular Vibration Spectrometer
- High-resolution Reflectometer
- High-wavelength Resolution SANS
- USANS

## CONDENSED-MATTER PHYSICS

### Synopsis

Solid-state and condensed-matter physics undergirds much of the technological progress and economic prosperity of the last fifty years. All indications are that novel new materials will continue to feed new technologies. Emerging topics of worldwide interest include complex solids based on organic molecules and low-dimensional solids such as quantum wires and dots. A persistent goal in solid-state and condensed-matter physics is to establish the ground state of relevant systems, which can be done by exploring excitations out of the ground state. Neutrons are often unique probes with which to accomplish this goal. Neutrons are required to study:

- Low-frequency excitations in heavy-fermion superconductors and quantum-critical and non-Fermi liquid behavior at very low temperatures and high magnetic fields or pressures,
- Elastic deformations, lattice distortions, lattice modulations and charge/spin density waves in complex oxides, such as the cuprate or ruthenate superconductors; using diffuse scattering and high-resolution quasi-elastic scattering to understand polaron structure and dynamics, in-homogeneities, and emergent phenomena such as striped-phases.
- Magnetic nanostructures, such as thin magnetic films, magnetic dot and antidot (hole) arrays, magnetic nanoparticles, and spin injection across magnetic/semiconductor interfaces. Such studies will rely on high-quality reflectometry and SANS using polarized neutrons and, in certain cases, neutron-polarization analysis. These studies are of vital importance for devices related to magnetic information storage, non-volatile RAM's, and spintronics. Magnetic and phonon excitations in thin films are almost impossible to study with current neutron sources owing to the low sample volume and (often) low-excitation energies, but could become feasible on the LPSS.

***Scientific and Programmatic Opportunities***

- Strongly Correlated Electron Systems
- Molecular Magnets
- Dynamics of Superlattices, Thin Films, Wires and Dots
- Spin-density Waves in Organic Materials
- Exotic Interactions
- Coupled Excitations
- Physics of Defects in the Dilute Limit
- Spin-glass Dynamics
- Quantum Phase Transitions

***Instrumentation Requirements***

- High-energy Chopper Spectrometer
- Cold-chopper Spectrometer
- Thermal-chopper Spectrometer
- High-resolution Back-scattering Spectrometer
- Medium-resolution Back-scattering Spectrometer
- High-resolution Spin-echo Spectrometer
- Chemical Single-crystal Diffractometer
- High-resolution Powder Diffractometer
- Magnetic Powder Diffractometer
- High-intensity Reflectometer
- Diffuse-scattering Diffractometer
- Polarized-neutron Reflectometer
- Reflectometer Equipped with Neutron Spin-echo Capability
- Milli-degree Temperature and ~10 T Magnetic Field Capability for Sample Environments

## MATERIALS AT HIGH PRESSURE, TEMPERATURE, AND STRESS

### Synopsis

Pressure is the cleanest method to exert a large thermodynamic perturbation on a material. Pressure imposes a large change in free energy yet directly compresses only electron density. Recent advances in super hard substances, ultra-tough nano-composites, metallic glasses, and materials with high-$T_c$ superconductive properties have demonstrated the importance of pressure studies in the discovery of exotic materials.

Beyond materials physics, however, high pressure-temperature (P-T) neutron studies are also fundamental to the geosciences, chemical sciences, and energy sciences. More importantly, high P-T characterization is essential to the Stockpile Stewardship Program, which seeks to model the dynamics of materials during a nuclear explosion based on the equation-of-state determined in laboratory experiments. Specifically, accurate information about the pressure derivative of the thermal expansion coefficient, the temperature derivative of bulk modulus, and the Gruneisen parameter are necessary to extrapolate existing laboratory data to the extreme high P-T's.

NxGens technology will produce four to nine times (at 2.5 MW), or sixteen to forty-four times (at 6 MW) more neutrons for diffraction experiments, and twenty-five to fifty-seven times more neutrons for radiography and tomography experiments compared to current sources. These advances will allow P-T neutron diffraction experiments in parallel with calorimetry, ultrasonic acoustics, neutron radiography, and neutron tomography.

The changes in structural, thermal, elastic, rheological, and mechanical properties associated with phase transformations in crystalline metals, ceramics, and minerals at high P-T conditions can be assessed in five different techniques *in situ* and *real-time* in a combined way, preferably in a single instrument:

1) Diffraction (to monitor structural/amorphous/melt phase transitions)

2) Calorimetry (to detect heat capacity, entropy, and enthalpy variations)

3) Ultrasound (to determine acoustic velocity)

4) Radiography (to measure solid deformation and sink/float speed in melts)

5) Tomography (to visualize the 3D-interior of bulk samples with 2D-sections)

The high beam intensity and higher resolution (granted by longer flight path) allow smaller samples (down to sub-mm), higher pressures *(up to 100 GPa)*, and higher temperatures. Diffraction studies at pressures up to 20 GPa (limited by sample size, which in turn is limited by neutron flux) and temperatures to 2000 K, can be performed now under deformation up to twenty-percent strain. *In situ* neutron imaging with 10 μm resolution can be combined with calorimetric measurements of chemical reactions and phase transformations. With spatially resolved focusing and collimating neutron optics, real-time studies of reaction kinetics and transformation dynamics can be integrated with techniques such as ultrasonic measurement of acoustic elasticity.

High P-T neutron diffraction can tackle long-standing geo-science problems such as magma migration, large-scale convection, mantle mineralogy, and the global hydrogen-carbon cycle. Furthermore, current disputes on the role of hydrous minerals in volcanic activity and deep earthquakes can be solved only through research on dehydration processes at high P-T. Mineral properties such as seismic velocity, melt viscosity, and phase density are essential parameters for modeling the dynamics and composition of the earth's interior. The subtle effect of cation substitution of $Al^{3+}$ and $Si^{4+}$ on the thermo-elasticity of mantle minerals, for example, requires a fundamental investigation at the crystal-chemistry level. The related rheological and visco-plastic properties can only be determined with combined techniques of neutron diffraction and neutron radiography in so-called "sink-float" experiments to measure stokes velocity.

High-pressure neutron studies are essential to energy and environmental studies. Hydrate materials formed at high pressure, for example, are relevant to technologies such as seafloor and permafrost recovery of methane ($CH_4$-$H_2O$ clathrate), ocean sequestration of carbon dioxide ($CO_2$-$H_2O$ clathrate), and hydrogen storage and transport ($H_2$-$H_2O$ clathrate).

High P-T neutron experiments provide a powerful means to address challenging materials science problems such as crystallization, texturing, amorphization, hydrogen bonding, and phase transformations. Bulk metallic glasses, for example, are traditionally studied with temperature (super-cooling) and chemical composition (substitution) as the controlling variables. Pressure, however, can also drive structural frustration and promote glass formation in alloys. Neutron probes at high P-T offer unprecedented opportunities to explore the forming process of bulk metallic glasses because of the contrast afforded by nuclear isotopes and the sensitivity to magnetic interactions. Moreover, neutron pair-distribution-function (PDF) analysis of atomic bonding can elucidate novel routes for producing bulk metallic glasses and nanocrystalline phases formed by transformation of amorphous metals.

The combination of neutron diffraction with calorimetric, ultrasonic, and neutron radiography and tomography is essential in these measurements. The determination of the P-V-T equation-of-state, thermochemistry, acoustic elasticity, and the phase diagrams of materials should all be performed to high-precision and high-accuracy by means of simultaneous integrated experiments. Some aspects of these methods have been successfully performed with synchrotron x rays. It is highly desirable to extend these techniques to neutrons for materials that are opaque to x rays or for which x-ray contrast is insufficient. Such developments are particularly important to the National Nuclear Security Administration and LANL missions.

***Scientific and Programmatic Opportunities***

- Amorphization, Crystallization, and Magnetization at High P-T Conditions
- Transition Kinetics and Phase Equilibrium Studies During High P-T Synthesis
- P-T Dependence of Hydrogen Bonding ion Hydrides, Hydrates, and Hydrous Minerals
- De-hydration and Re-hydration Processes and Associated Kinetics and Dynamics
- Storage of Volatiles in Minerals to Constrain Global Hydrogen-carbon Budget
- Structure and Texture of Metal Alloys with High P-T Metallurgy Implications
- Texture Evolution During Structural Phase Transformations
- PDF Measurements of Density and Bonding in Melts and Fluids
- Compressibility and Thermal Expansion of Melts and Fluids Under High P-T
- Viscosity and Rheological Deformation of Metals, Ceramics, and Minerals
- Characterization of the Yield Strength and Constitutive Properties as F(P, T)
- Ultrasonic Interferometry Measurement of Elastic Properties at High P-T
- Changes in the Thermodynamic Properties of Materials During Heating and Pressurization
- Phase Diagram and Crystal Structure of Ices and Clathrate Hydrates Under P, T
- EOS of Materials of Importance to Materials Physics and Computer Simulation
- Influence of Pressure On Nanomechanics and Nanosynthesis at High P-T
- Porous-flow, Permeability, and Transport Properties in Geo-Hydrological Conditions
- Fracture Propagation and Crack Distribution of Bulk Materials
- Magnetic and Superconductive Properties of Materials as a Function of P-T
- Pressure Dependence of the Chemistry of Bio-materials

***Instrumentation requirements***

- Engineering Diffractometer and Tomography.
- Chopper Spectrometers
- Backscattering Spectrometer, 0.8 – 1.5 μeV Resolution
- Engineering Diffractometer for Deformation and Damage
- High-resolution Powder Diffractometer (Texture)
- High-intensity SANS

## STRUCTURAL MATERIALS SCIENCE AND ENGINEERING

### Synopsis

Advances in materials science and engineering consistently evoke new technologies that drive economic wealth and sustainable growth. These disciplines also underlie development of new energy sources and the reduction of pollution. Neutron scattering provides structural and dynamical information over an enormous range of length and time scales. Presently, however, data acquisition is often too slow for *in situ* and real-time studies or process monitoring. Modern technologies demand information from smaller sampling regions often buried in complex environments monitored in real-time under various external fields. Only neutron scattering can meet these demanding requirements.

Currently, scattering research on structural materials at LANL falls into two distinct categories:

1) The response by metals, rocks, ceramics, and glasses to applied stress and temperature, and
2) Residual stress due to thermo-mechanical processing treatments, such as forming, welding, or annealing.

The first area will provide a physical understanding of the development of mechanical properties of complex materials and lead to rational design of the next generation of materials. The second area addresses engineering design to optimize residual stress, microstructures, and failure properties.

The future of engineering-strain studies lies in understanding more complex materials observed in real-time during processing. *In situ* loading measurements at spallation neutron sources have contributed greatly to the understanding of deformation mechanisms in relatively simple metals and simple composites. The future lies in complex materials, such as uranium and plutonium, and in shape-memory alloys, which deform by phase transformations.

Nanocomposites exhibit superb mechanical response compared to micro-scale composites. One of the great challenges is to understand how the large gains are realized to facilitate rational design of nanocomposites. The future lies in measuring the residual stresses real-time during the processing, and under conditions that simulate operational environments, including stresses that develop during welding, forming, and during thermal processes such as quenching.

Nuclear components are formed from complex materials, such as explosives and plutonium, as well as ceramics and other materials whose deformation is not well understood. Also, residual stresses are bound to exist near the bonding of dissimilar metals. *In situ* neutron diffraction measurements at temperature will lead to physics-based models of the micro-mechanical deformation of these materials. The goal is to replace current empirical models by predictive codes and models based on fundamental physics.

The key to productive research is increasing the available neutron flux. Current research is about one order-of-magnitude away from realistically performing real-time strain measurements during processing. Measurements that currently take three hours to complete need to be done in twenty seconds. Increased flux will allow researchers not only to witness an effect (e.g. a stress induced phase transformation) but also to characterize its behavior as a function of extrinsic parameters such as temperature and pressure.

***Scientific and Programmatic Opportunities***

- Structure and Dynamics of Thin-film Lubricants
- Deformation and Damage Mechanisms in Realistic Fatigue Cycles
- Energy and Conversion Devices Especially Time-resolved Phenomena in Fuel Cells
- Spin Structures and Hysteretic Behavior of Magneto-electronic Devices Covering a Large Parameter Space of Temperature and Magnetic Fields
- Process Monitoring and Optimization of Large Engine Parts in Operation, Including Time Dependence
- Diffusivity of Protons in Thin Films with Switchable Properties with Respect to Sample Volume.
- Hydrogen Embrittlement in Nuclear Power Materials
- Materials for Desalination Processes
- Tomography and Bragg-edge Tomography (Process Monitoring)
- Cold Neutron Spectroscopy (Monitoring Hydrogen)

***Instrumentation requirements***

- Backscattering Spectrometer, 0.8 – 1.5 meV Resolution (in particular for lubrication)
- Engineering Diffractometer (Deformation and Damage)
- High-resolution Powder-diffractometer (Energy Conversion)
- High-resolution Reflectometer (Magneto-electronics)
- High-intensity SANS

## MINERAL SCIENCES, EARTH SCIENCES, ENVIRONMENTAL SCIENCES, AND HUMAN SCIENCES RESEARCH

### Synopsis

Neutrons play a vital role in mineral and Earth science. The prevention of hazards posed by volcanic eruptions and earthquakes is a major science-driver for understanding of matter under the conditions within the mantle. Also, continental shelf methane clathrates, which could serve as a basis for future energy supply, are well suited to neutron analysis. Geological and geophysical questions about the history and genesis of the Earth promise to shed light on planetary formation. Finally, fingerprinting of archaeological materials and their non-destructive analysis helps to understand the cultural and biological evolution of diverse populations.

Neutron scattering is essential to characterize minerals consisting largely of hydrogen, such as ice and hydrate clathrates. More than one order-of-magnitude of hydrogen is stored in hydrous minerals in the mantle than exists in the whole hydrosphere (oceans & atmosphere). Water on Mars is largely bound hydrous minerals, underlining the paramount importance of the understanding of formation, stability and interaction of such minerals.

The role of hydrogen on the deformation and fracture mechanisms is investigated exceptionally well with neutrons. Similar to engineering measurements, neutrons can measure *in situ* deformation of rocks. More intense neutron beams will also allow spatially resolved measurements of fracture mechanics, a field of great interest for prediction of earthquakes.

Neutron radiography and tomography have many applications in earth science. Higher neutron flux means higher resolution. Transport in porous media, of interest to gas and oil prospecting, can be studied if sufficient neutron flux is available. Determination of the viscosity of rock melts, a fundamental parameter for modeling of magmas and lavas, is also possible with high-resolution neutron radiography. Density measurements of melts at high pressures are important parameters for magma models and are only obtainable from neutron high-pressure experiments.

***Scientific and Programmatic Opportunities***

- Pressure-induced Spin Dynamics and Spin Collapse of Iron
- Molecular Dynamics of $H_2O$, OH and $CO_2$ Under Earth-Mantle conditions
- Geochemical Synthesis of Extreme Materials
- *In Situ* Diffraction and Spectroscopy of Methane Clathrates
- Time-resolved Neutron Radiography and Tomography of Fluids and Melts Under Earth Mantle Conditions
- *In Situ* Measurements of Stress Strain Partitioning During Rock Deformation
- Influence of Stress and Development of Texture Upon Deforming Geo-Materials
- High-pressure Behavior of Materials Especially Geomaterials
- Fingerprinting and Non-destructive Analysis of
- Archaeological Materials

***Instrumentation requirements***

- Chopper Spectrometers
- Molecular Vibration and eV Spectrometer
- High-resolution Powder Diffractometer
- Engineering Diffractometer and Tomography

## CHEMICAL STRUCTURE, KINETICS, AND DYNAMICS

### Synopsis

The understanding of materials is based upon a detailed knowledge of their structure and dynamics at the atomic and molecular level. Single-crystal and powder diffraction, small-angle neutron scattering and reflectometry, inelastic and quasi-elastic spectroscopy, and neutron spin-echo measurements all contribute to understanding of chemical structure, kinetics, and dynamics. With current neutron instrumentation, however, the instrument (not the sample) generally determines the time scales of experiments; similarly, sample size is often dictated by flux limitations.

Technological issues range from fuel cells, batteries and hydrogen storage to smart materials that respond to their environment. New advanced materials may be studied in bulk (e.g. for chemical processing) or as thin films to build new devices. All these developments require an extension of the analytical tools to study chemistry and chemicals in small quantities, in complex mixtures and under the conditions of imposed external environments such as stress, temperature, and pressure.

***Scientific and Programmatic Opportunities***

- Kinetics of Chemical Reactions
- *In Situ* Observation of Catalytic Processes
- Energy Storage and Conversion Processes
- Electrochemistry at Surfaces, Especially in Fuel Cells
- Hydrogen Bonding and Proton Dynamics in Supramolecular Chemistry
- Hydrogen Storage in Materials
- Colloidal Chemistry and Double Layer Structure
- Nanoscale Materials for Photonic and Electronic Applications
- Diffusion in Porous Materials
- Quantum Dynamical Processes

***Instrumentation requirements***

- High-resolution Powder Diffractometer
- High-energy Chopper
- Molecular Vibration Spectrometer
- Chemical Single Crystal Diffractometer
- High-resolution Neutron Spin Echo
- Cold and Thermal Choppers
- Backscattering Spectrometers
- High-intensity Reflectometer
- High-Q Powder Diffractometer
- Single-pulse Diffractometer
- Magnetic Powder Diffractometer

## LIQUIDS AND GLASSES

### Synopsis

Neutron scattering is a key experimental technique in the study of structure and dynamics of liquids and glasses. Neutrons will play the central role in studies using multiple complementary techniques: x-rays, light scattering, and NMR; each providing information on specific aspects of the structure or dynamics of complex disordered materials. Such a coherent approach will elucidate physical processes in disordered materials, but also enhance the ability to exploit atomic-scale structure and dynamics for the production of materials with optimized properties. Measurements covering a wide range of length scales and energies are essential.

The current limitation in isotopic substitution experiments is instrument instability rather than achievable statistics. Gains in count-rate can therefore produce a linear gain in experimental capability. For phase diagram studies or kinetics, the gain is also linear.

#### *Scientific and Programmatic Opportunities*

- Influence of Molecular Entities on Solvent Structure in Solution as a Function of Multiple Thermodynamic Parameters (Concentration, Temperature, Pressure, etc.)
- Multicomponent Magnetic Metallic Glasses, Ion Conductors with Low Concentrations of Mobile Ions, Impurities, and Dopants in Optical Fibers
- Crystallization, Nucleation, Order-disorder Transitions, Kinetics, Aging, and Processing of Nanocrystalline Materials
- Element-specific Atomic Dynamics of Disordered Matter (Using Isotopic Substitution)
- High-information Bandwidth Atom-specific Dynamics (Isotopic Substitution, Wide Q-ω Range, Brillouin Scattering), Combined with Modeling and Simulation Studies (making movies!)

#### *Instrumentation Requirements*

- Liquids Diffractometer
- SANS
- High-intensity Reflectometer.
- Chopper Spectrometers
- Backscattering Spectrometers
- Spin-echo Spectrometers

# Appendix B: LANSCE's Current Capabilities in Neutron Scattering

*The Lujan Center at LANSCE produces the highest-peak neutron flux in the world.* This performance derives in part from the Center's unique coupled-moderator target design, adopted by all new, second-generation short pulse spallation sources around the world (Spallation Neutron Source, Japanese Proton Accelerator Research Complex, ISIS, European Spallation Source, and Chinese Spallation Neutron Source). LANSCE also leads in development of instruments desined to utilize these new moderators. The Protein Crystallography Station (PCS), for example, gives unprecedented performance for structural biology.

The Lujan Center's coupled moderators, in conjunction with state-of-the-art instruments, assure that the Lujan Center will remain competitive as second-generation sources come on-line. The spallation Neutron Source is projected to be the most powerful short pulse source when fully operational in 2009.

As the need to understand the complexity of materials increases, understanding their properties of structure on larger scales, and their dynamics at lower energies, becomes more important. It is the trend toward understanding materials complexity that drives the need for a NxGens long pulse spallation source. With refurbishment, the LANSCE facilities are poised to move into the future of materials science and bioscience research.

**THE LUJAN NEUTRON SCATTERING CENTER**

# Appendix C: Comparative Analysis of Present and Future Neutron Scattering Facilities

When the Spallation Neutron Source (SNS) begins operating, raw power will not necessarily be a differentiating disadvantage for the Lujan Center. Rather, the Center's role in the national neutron scattering program must play to the Center's strengths in cold neutron flux and associated instrumentation. The cold neutron mission not only satisfies scientific drivers but also exploits the 20 Hz beam pulse repetition rate. After enhancement, the Lujan Center will remain within a factor of three to ten times the SNS in the cold-neutron spectrum, with the added advantage of wide-bandwidth enabled by low repetition rate. *Therefore, the Lujan Center will retain its status in the SNS-era as a premier neutron facility and as the only source devoted to science relevant to defense research.*

The construction of a NxGens-prototype long pulse spallation source will provide the nation with a neutron scattering resource that is quick and relatively inexpensive to build, and comparable to the SNS in cold neutron applications. In addition, the enhanced LANSCE facility will accommodate future upgrades at minimal cost—*LANSCE will be positioned to develop a full-power NxGens Generation-III long pulse spallation source (Table 1).*

The comparative study presented here documents the specific performance expectations calculated using the instrument simulation database developed by the ESS design team.[1] Several operating conditions for LANSCE were evaluated including the current Lujan Center operating at 20 Hz short-pulse mode delivering 150 kW, and the NxGens 660KW with a 33 kJ/pulse LINAC operating at 20 Hz with 2 ms pulses. The accelerator parameters for the 2.5 MW NxGens will be achieved by retaining LANSCE's ~21 mA front-end peak current and using a superconducting coupled-cavity LINAC to achieve 3 GeV final proton energy.

The full NxGens potential using current LINAC technology is 100 mA peak current at 3 GeV final beam energy to yield 300 kJ/pulse over 1 ms pulse length—6MW at 20Hz. This configuration surpasses the 2.5 MW enhancement option in Table 1 in time-average flux by a factor of about 2.4 and in peak flux by a factor of 4.6. The 6 MW calculation is included in the table since it represents an ultimate scientific destination for neutron scattering at LANL.

Table 1 includes full-power SNS as well as the (unfunded) SNS Long Wavelength Target Station (LWTS: 10 Hz, 230 kW). For comparison, the table provides a state-of-the-art facility in 2005 (the higher of either the Institut Laue-Laugevin—the current most intense reactor source—or ISIS—the current highest power spallation source, which produces 50 Hz at 200 kW.)

In Table 1 the figure-of-merit is the neutron intensity on the sample relative to the value expected at SNS (defined as 1.0) under conditions of identical resolution and dynamic range. In all cases, state-of-the-art instrument design was assumed in order to reflect the true capabilities of the respective sources. Thus for target stations with 10 or 20 Hz repetition rate and for cold neutron chopper spectrometers, repetition-rate multiplication (RRM) was assumed, which allows more efficient data collection. The performance indicated for the existing sources is often superior to that actually achieved since existing instruments often lack enhancements such as neutron guides, up-to-date reflecting coatings, full detector coverage, and optimal moderators.

The table demonstrates the complementary nature of long pulse spallation (LPSS) and short pulse spallation (SPSS) sources of roughly comparable power. An eventual second target station at SNS (LWTS) will increase the number of beam lines, but not their performance.

[1] The European Spallation Source Project, Volumes I-IV, The ESS Council, Druckerei Plump OHG, 2002, Medium to Long-Term Perspectives of Neutron Based Science in Europe, ESFRI, 2003.

The basis of instrument performance evaluation is the brilliance and shape of the neutron pulses emitted by the moderators. The pulses are shown in Figure 1 for 6 Å wavelength cold neutrons. The curves were calculated using an analytic approximation based on a synthesis of published neutronics calculations at LANSCE, SNS, and the Japanese Particle Accelerator Research Complex.

The model is known to agree with the measured line shapes at LANSCE's Lujan Center to better than twenty-percent accuracy for both peak and time-average flux. All options assume liquid-H2 cold moderators in state-of-the-art geometries.

In the SNS-LWTS proposal a number of possibilities are identified that could enhance the neutron flux (e.g. enhanced size moderators, tungsten target, cooled reflector).

These options need to be studied in detail. With the exception of a solid-methane-cold-moderator, which is limited to small source powers, these potential enhancements apply almost equally to all spallation sources. For this reason only the distinctive impact of solid methane as the moderator at SNS-LWTS is considered (even though its feasibility has not yet been fully demonstrated).

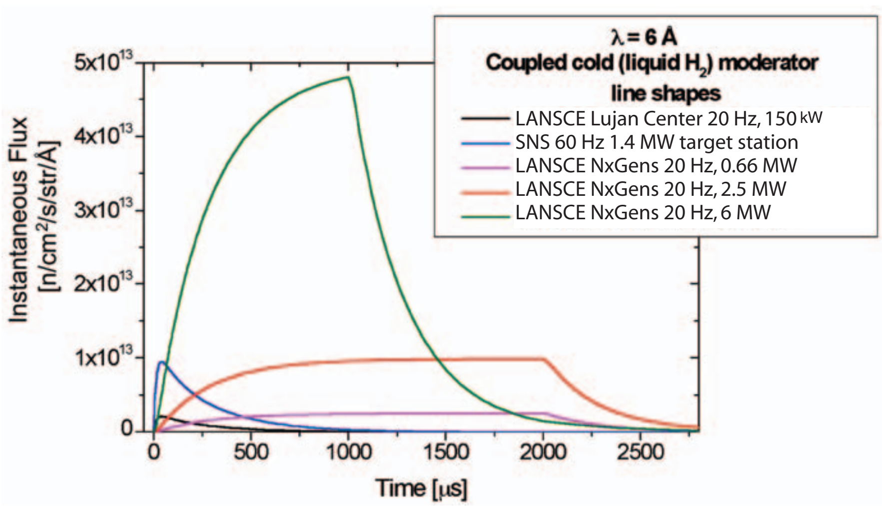



**Figure 1.** Cold neutron line shapes for various NxGens spallation source options at LANSCE compared with two SPSS source: the Lujan Center (as of today) and SNS (in construction). The integrated flux of the NxGens pulses is fully used in applications requiring moderate-wavelength resolution, such as small-angle scattering. In applications requiring short-wavelength resolution (e.g. medium- and high-resolution diffraction), pulse-shaping choppers will be used to produce pulses with variable lengths, including shorter ones than those available at SPSS. These 6 MW calculations represent the ultimate NxGens potential at LANSCE.

| TABLE 1: SOURCE PERFORMANCE AT LANSCE BENCHMARKED AGAINST SNS. | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Instrument** | **Lujan @ 150 kW** | **SNS LWTS** | **SNS (Benchmark)** | **NxGens @ 660 KW** | **NxGens @ 2.5 MW** | **NxGens @ 6 MW** | **State-of-the-Art Facility 2005** |
| Variable Cold Chopper (High-Intensity) | | 0.6 | 1 | 1.2 | 5 | 12 | 0.5 |
| High-Resolution Neutron Spin Echo | | 0.7 | 1 | 1.2 | 5 | 12 | 0.9 - 2 |
| High-Intensity SANS | 0.3 | 0.6 | 1 | 1.2 | 5 | 12 | 0.7 - 1.5 |
| Focusing SANS | | 0.6 | 1 | 1.2 | 5 | 12 | 0.7 - 1.5 |
| Wide Angle Neutron Spin Echo | | 0.6 | 1 | 1 | 4.2 | 10 | 1 |
| High-Intensity Protein | 0.2 | 0.4 | 1 | 0.75 | 3 | 7.2 | 0.7 |
| Magnetic Powder | 0.2 | 0.5 | 1 | 0.4 - 0.7 | 2 - 2.8 | 4.8 - 12 | 0.1 |
| High-Resolution Powder | 0.1 | 0.5 | 1 | 0.2 - 0.5 | 0.7 - 2 | 4.9 | 0.09 |
| High-Intensity Reflectometer | 0.1 | 0.30 | 1 | 0.50 | 2 | 4.8 | 0.09 |
| Tomography (Full Beam) | | 0.2 | 1 | 0.45 | 1.8 | 4 | 3 |
| Single Pulse Diffraction | 0.1 | 0.25 | 1 | 0.2 - 0.4 | 1.60 | 2 - 7 | 0.1 |
| Engineering Diffractometer | 0.07 | 0.3 | 1 | 0.1 - 0.3 | 0.4 - 1.2 | 1.8 - 5 | 0.09 |
| Cold Chopper | | 0.6 | 1 | 0.2 | 0.8 | 3.8 | 0.1 |
| Variable Cold Chopper (High-Resolution) | | 0.6 | 1 | 0.2 | 0.8 | 3.8 | 0.1 |
| Chemical Single Crystal | 0.05 | 0.5 | 1 | 0.2 | 0.8 | 3.8 | 0.15 |
| High-Resolution Protein | | 0.50 | 1 | 0.2 | 0.8 | 3.8 | 0.15 |
| Liquid Diffractometer | | 0.25 | 1 | 0.03 - 0.2 | 0.1 - 0.8 | 0.5 - 4 | 0.15 |
| Bragg-Edge Tomography | 0.03 | 0.25 | 1 | 0.13 | 0.5 | 2.5 | 0.1 |
| Thermal Chopper | 0.03 | 0.18 | 1 | 0.13 | 0.5 | 2.4 | 0.1 |
| Backscattering 0.8 μeV | | 0.3 | 1 | 0.9 | 0.35 | 1.70 | 0.13 |

# Appendix D: Materials Test Station

***Experimentation on fuels and materials is a priority.*** A wide variety of potential fuels and materials must be researched, characterized, fabricated, irradiated, and examined. Previous research shows that fuels and materials behaviors are a function of the burn-up, displacements per atom (dpa), and helium production. Independent of these parameters, but equally important, is the temperature the materials are irradiated, and their neutron spectrum. Thus, irradiation and testing in prototypic environments is ultimately needed. To obtain irradiation data in a timely manner, accelerated testing is desirable. For example, although the neutron intensity of the Lead Fast Reactor is only 0.7 x $10^{15}$ n/cm$^2$/s, the reactor is designed to operate twenty years without refueling. The neutron fluence on the cladding is 4 x $10^{23}$ n/cm$^2$ at the end of life. Ultimately, to prove the efficacy of the materials in a test environment, much higher neutron intensities (such as 3x- or 4 x- $10^{15}$ n/cm$^2$/s) are required for accelerated testing.

Isotope production capabilities are limited. A study performed in 1999 generated a preliminary list of prospective isotopes needed in the U.S. for advanced medical and industrial needs. These unique isotopes can be produced at the LANSCE Materials Test Station (MTS). Further-more, these will be produced while running parasitically; with little or no impact on the materials irradiation mission.

The neutron-rich isotopes shown in Table 1 have a market value of several million U.S. dollars per year, and are complementary to the neutron-poor isotopes produced at the current LANSCE isotope production facility that extracts a portion of the LANSCE beam at 100 MeV.

*A wide variety of potential fuels and materials must be researched, characterized, fabricated, irradiated, and examined. Irradiation and testing in prototypic environments is ultimately needed. To obtain irradiation data in a timely manner, accelerated testing is desirable.*

**TABLE 1. ISOTOPE PRODUCTION**

| Nuclide | Annual Need (million curies) | Possible Production Rate (million curies) |
|---|---|---|
| 26 Al | 0.002 | 0.0059 |
| 67 Cu | 12,000 | 173,000 |
| 68 Ge | 5,000 | 2,500 |
| 82 Sr | 22,000 | 81,000 |
| 88 Zr | 2,000 | 17,600 |
| 88 Y | 2,000 | 8,800 |
| 103 Pu | 9,000,000 | 280,000 |

## THE MATERIALS TEST STATION

Area A, a large experimental area at the east end of the LANSCE accelerator (Figure 1) will house the MTS. A shielded beam line runs through the middle of the building at approximately five feet above the floor. This beam line produces high-energy particles (muons, pions) for medium energy science experiments, by passing the beam through two graphite targets at target stations A-1 and A-2 respectively. Secondary beam lines and spectrometers are stationed adjoining the graphite targets. The primary and secondary beam lines are shielded with a combination of iron plate and concrete blocks. The target cells are accessible through side ports (for graphite target maintenance), and from the top, through large rollback doors. The preferred location for the MTS is the A-2 target station, providing the best experimental access for the future.

## MATERIALS TEST STATION CONFIGURATION

The MTS configuration is shown in Figure 2. The spallation target, reflector and sample irradiation components are all contained in a vacuum vessel that eliminates the production of

**TABLE 2. PEAK NEUTRON INTENSITY**

| Year | Ave. Beam Current Delivery to Area A (mA) | Beam Energy (MeV) | Beam Power (kW) | Peak Fast Neutron Intensity (n/cm$^2$/s) |
|---|---|---|---|---|
| 2008 - 2012 | 0.72 – 1.0 | 800 | 576 – 800 | **1 x $10^{15}$** |
| 2012 - beyond | 2.25 | 800 | 1800 | **2.0 x $10^{15}$** |

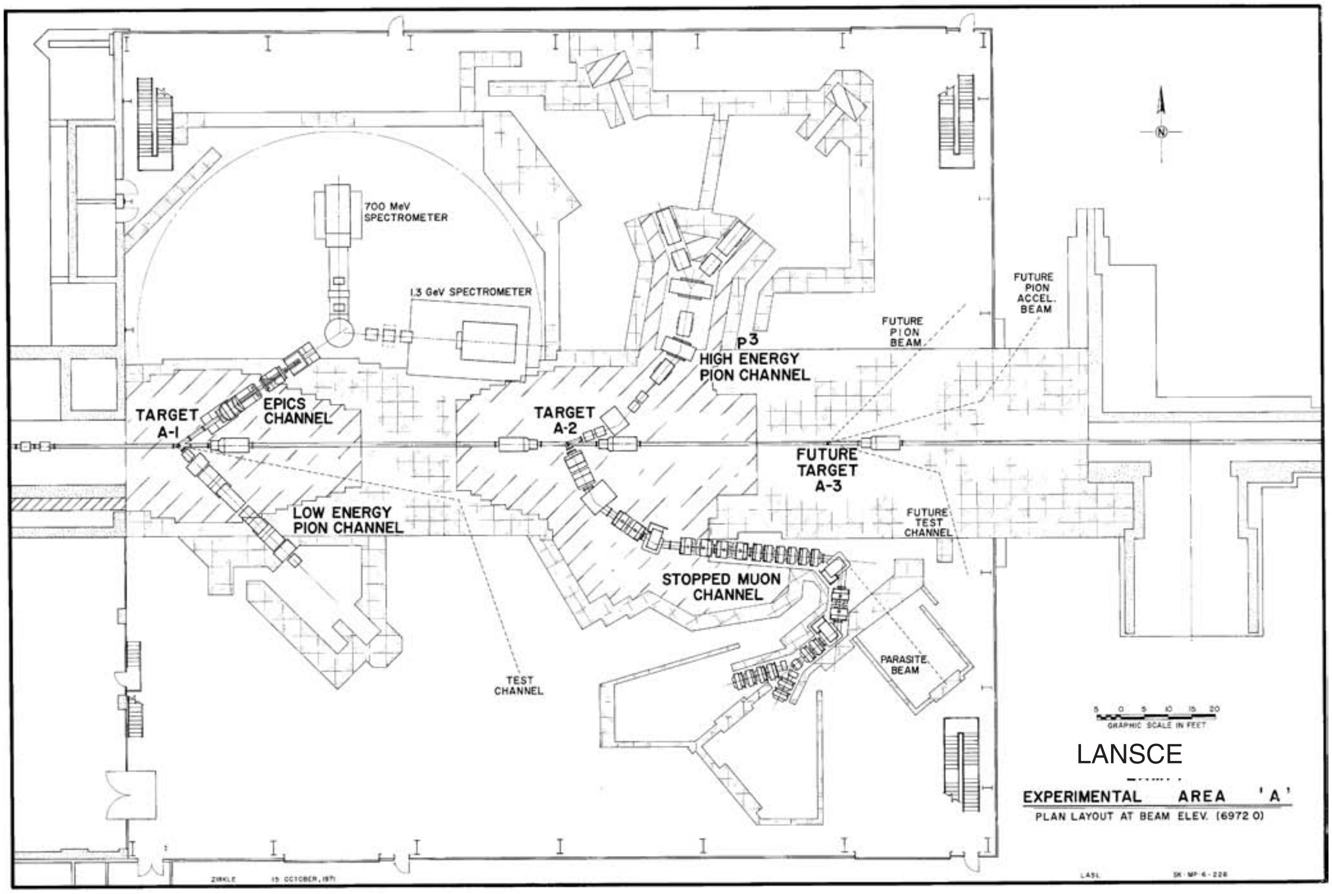



**Figure 1**. Experimental Area A shows the locations of the existing A-1 and A-2 target stations. The preferred location for the MTS is A-2.

contaminated air. The initial target configuration will employ proven water-cooled tungsten technology, which is used in several applications at LANL and elsewhere. The spallation target assembly is introduced horizontally, whereas the sample assembly containing irradiation experiments is introduced vertically from the top. Both assemblies are designed for ease in maintenance and replacement. Thus, to accommodate higher power levels will require minimal changes and cost. The sample assembly will provide temperature control to the experiments, and with future additions will accommodate special coolant needs with closed loops. Because the MTS is not a reactor, there is no possibility of reactivity feedback effects of an experiment on the neutron source, and therefore eliminates this safety concern.

The Area A building contains all the utilities needed to service the MTS. The existing crane is sufficiently large to remove and replace the shield blocks and plates and placement of the major components. Figure 3 shows the MTS installed in the A-2 position along with the primary heat removal system. Future missions for high-energy neutron radiography for stockpile applications and long pulse spallation source will be accommodated with the addition of beam lines, as shown in Figure 4.

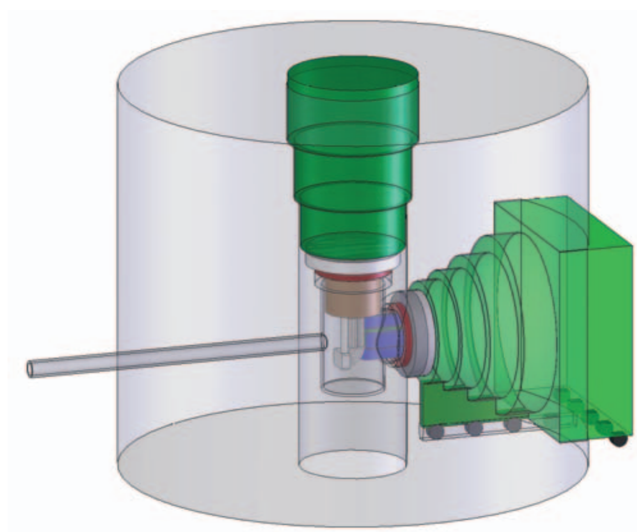


**Figure 2**. The MTS is configured with a small vacuum tank connected to the beamline. The spallation neutron source is introduced horizontally, and the materials experiment from the top.

The pulsed nature of the $H^+$ beam delivered to Area A (the beam is on for roughly 1 ms followed by approximately 7 ms with the beam off) allows the beam to be alternately delivered to one of two positions on a split target. This operating scenario is well within the capability of existing magnet technology. Alternating the beam spot position between two points on the split target produces a greater and more uniform neutron flux in a flux-trap region located between the target sections.

The footprint of the proton beam is divided into two rectangles, one on either side of the central fuel irradiation region (see Figure 5). Additional irradiation volume is accommodated on the outside of the beam footprints, where the flux is lower than in the central irradiation region. A fast-spectrum flux intensity of 1 x $10^{15}$ n/cm$^2$/s per mA of beam current is achievable in the central irradiation region.

The neutron spectra of typical fast reactors and the MTS are similar (Figure 6), with the caveat that the MTS has an additional high-energy tail beyond 10 MeV. These

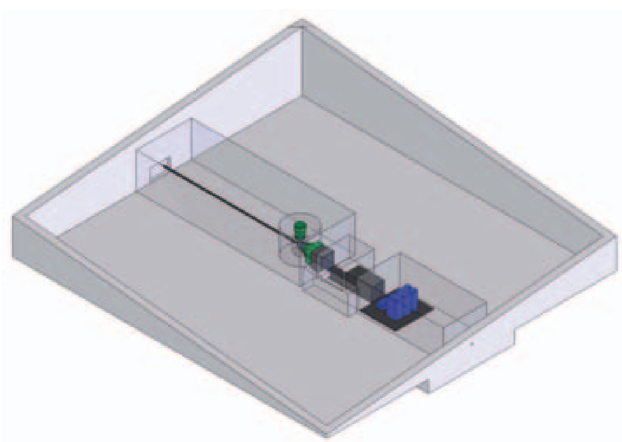


**Figure 3.** Materials Test Station with heat removal system installed at position A-2 in Area A.

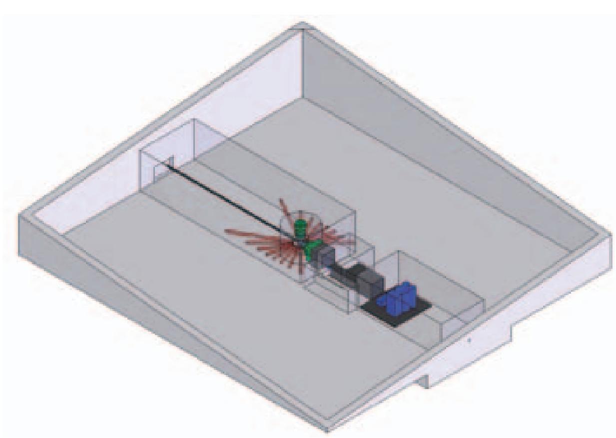


**Figure 4.** Materials Test Station with the addition of beam lines.

high-energy neutrons produce a moderate amount of hydrogen and helium gas in structural materials, which leads to higher He-to-dpa ratios for structural samples placed in the MTS, as compared with that seen in a typical fast-spectrum reactor. As an example, the He-to-dpa ratio in the Fast-Flux Test Facility (FFTF) reactor is 0.2 to 1.0 appm/dpa, whereas this same ratio in the MTS ranges from 0.5 to 10.0 appm/dpa, depending on the irradiation location. Although the high-energy neutrons are not prototypic of fission systems, they are prototypic of fusion systems.

The fact that MTS can achieve high helium generation rates at certain locations in the design demonstrates the broader application of the MTS to fusion energy systems which generate 10 appm He per dpa. Depending on the temperature of irradiation, helium generation will have minimal effects on structural material performance until 100 to 1000 appm is reached. Thus the MTS will provide prototypic material irradiations for fission systems for dpa and appm values typical of what is expected.

To address isotope production needs, special target materials will be introduced in the tungsten spallation neutron source. The tungsten neutron source is comprised of a large number of parallel plates. Each plate is clad in tantalum or stainless steel. Inclusion of a few special isotope production target plates will have a minimal impact on overall neutron production for materials irradiation, and will provide a source of special isotopes that can be produced in the 800 MeV proton beam. In addition, the tungsten neutron source itself will provide a large number of special isotopes as spallation products grow in during irradiation. The neutron source will be replaced approximately every two years, providing another source of isotopes that can be "mined" with chemical processing.

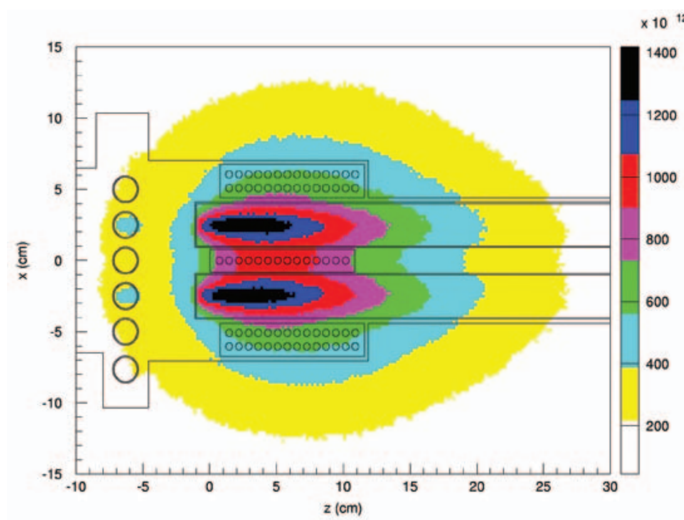



**Figure 5.** The top view of the neutron intensity surrounding the split spallation target. Fast neutron (E > 0.1 MeV) flux intensities reach 1 x $10^{15}$ n/cm$^2$/s per mA of current at 800 MeV.

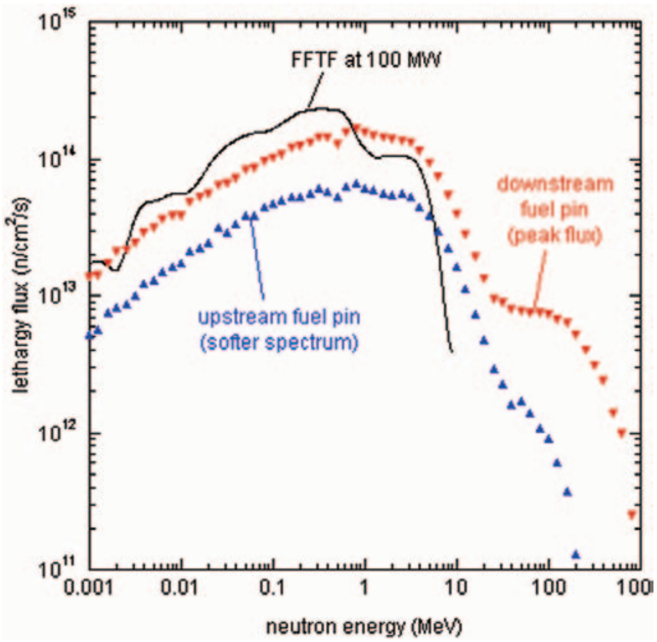



**Figure 6.** Comparison of the MTS spectrum to a typical fast-reactor.

In addition, a closed loop rabbit system can provide the capability to produce short-lived radioisotopes for the weapons program.

The MTS design accommodates a 1 mA beam on target. At 800 MeV, this translates into 800 kW of beam power. Because the beam is shared with the LANSCE Isotope Production Facility, the beam current will vary between 0.72 and 1.0 mA during normal operation. With the current design, a fast-spectrum flux intensity of 1 x $10^{15}$ n/cm$^2$/s per mA of beam current is achievable in the central irradiation region. During conceptual design, options will be considered to increase this intensity further.

Other than Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR), which contains very limited irradiation capability, the Advanced Test Reactor (ATR) at Idaho National Engineering and Environmental Laboratory is the only operating test reactor in the U.S. today. The ATR specializes in producing high-intensity thermal neutrons for fuels and materials irradiations. To complement the ATR, and to prove the performance of materials and fuels in a fast neutron spectrum (> 0.1 MeV) the LANSCE-MTS will fill the near-term irradiation needs through 2025. The relative attributes of the two facilities are listed on Table 3.

The MTS includes a spallation target; reflector and sample irradiation components are all contained in a vacuum vessel. The initial target configuration will employ water-cooled tungsten technology, which is well proven in applications at LANL and elsewhere. The spallation target assembly is introduced horizontally, whereas the sample assembly containing irradiation experiments is introduced vertically from the top. Both assemblies are designed for ease in maintenance and replacement. Thus, to accommodate higher power levels will require minimal changes and cost. The sample assembly will provide temperature control to the experiments, and with future additions could accommodate special coolant needs with closed loops. The neutron spectra of typical fast reactors and the MTS are similar and with the initial beam power of 800 kW, a fast-spectrum flux intensity of 1 x $10^{15}$ n/cm$^2$/s is achievable. With upgrades in beam power, this intensity can be easily doubled. At a cost of $36M – $50M the LANSCE-MTS is a cost-effective and timely solution to provide fast neutron irradiation capability for the United States.

**TABLE 3. COMPARISON OF IRRADIATION ATTRIBUTES OF ATR AND LANSCE-MTS**

| Parameter | ATR | LANSCE-MTS |
|---|---|---|
| High-intensity Fast Neutrons | | X |
| High-intensity Epi-thermal neutrons | X | X |
| High-intensity Thermal Neutrons | X | |
| High-intensity Protons (applicability to ADS) | | X |
| High dpa | X | X |
| High Helium Generation (applicability to fusion systems) | | X |
| Water Coolant | X | X |
| Capability for Liquid Metal Coolant | | X |
| Irradiation Temperature Control | X | X |
| Flux Uniformity Over Fuel Rodlets (up to 11 cm) | X | X |
| Flux Uniformity Over Fuel Rods (greater than 11 cm) | X | |
| High-Fuel Burn-up | X | X |
| High-Fuel Power Density (greater than 500 W/cc) | | X |

# Appendix E: The Rare Isotope Accelerator

## INTRODUCTION

LANSCE enhancements create a portal for the eventual development of a Rare Isotope Accelerator (RIA).[1] The cost of building an RIA at LANSCE would be reduced over a green-field site.

The RIA is recommended as the highest priority for new major construction for nuclear physics in the DOE/NSF Nuclear Science Advisory Committee's 2002 Long Range Plan.[2] An RIA would be dedicated to producing and exploring isotopes not found naturally on earth. The cost of this new facility is estimated to be as high as one billion dollars and would provide physicists with high-quality beams of almost all isotopes. An RIA would permit research in four main areas: nuclear structure, nuclear astrophysics, nuclear reactions, and fundamental interaction physics.

## NUCLEAR STRUCTURE

The RIA will provide a unique opportunity to explore in detail the structure of nuclei far from stability. At the limits of nuclear stability previously unexplored aspects of the strong interaction between nucleons will be probed. Key questions on the properties of the nucleon-nucleon interaction, away from the line of stability, include what is the:

- Strength of the spin-orbit interaction?
- Strength of the three-body force?
- Density dependence of the nuclear symmetry energy?
- Role of the pairing interaction?
- Magnitude of the shell gaps?
- Effect of weak binding energies on nuclear properties?

Knowledge of how these aspects of the nuclear interaction manifest themselves in unstable nuclei will allow a unique understanding of how and what type of nuclear matter is formed under the extreme conditions seen in astrophysics environments.

The very weak binding energy of the last one or two neutrons in such nuclei gives rise to the so-called "neutron halo nuclei" where the neutron radius extends far beyond the proton radius. These halo nuclei exhibit unusual properties, including low-lying pygmy electric dipole resonances. In addition, moving away from N=Z nuclei the contribution to the nuclear binding energy from the symmetry energy increases, which can affect neutron-proton radii differences. Predictions for the density dependence of the symmetry energy for relativistic mean field calculations differ considerably from those for non-relativistic type of nuclear matter that can form in such extreme environments.

The strength of the spin-orbit interaction is directly tied to the strength of the three-body force. Light p-shell nuclei *ab initio* calculations show that the three-body force accounts for about half of the spin-orbit strength. Calculations suggest that as the neutron to proton ratio becomes large the mean field becomes very shallow and the spin-orbit strength is significantly reduced. However, it is not clear how the two-body versus the three-body contributions to the spin-orbit strength vary moving away from the valley of stability. The most important effect of quenching the spin-orbit strength is its effect on shell gaps and magic numbers. If the shell gaps near the neutron dripline are considerably smaller than in spherical stable nuclei there are very large differences predicted for rapid neutron capture (r-process) abundances.

## NUCLEAR ASTROPHYSICS

The abundance patterns of nuclear isotopes are key signatures for understanding different astrophysical environments. For example, the nucleosynthesis patterns of the Big Bang, supernovae, ABG stars, and accreting neutron stars are each unique and are direct probes of the underlying astrophysics involved. Deducing the relevant astrophysical information, such as the site or the temperature for the nucleosynthesis process in question, requires knowledge of the nuclear properties of the nuclei involved. The RIA will enable the nuclear physics measurements needed to address the key astrophysical questions for explosive nucleosynthesis of the:

- rp-process (rapid proton capture)
- r-process
- s-process (slow neutron capture)

[1]See http://www.sc.doe.gov/production/henp/np/nsac/nsac.html
[2]See http://www.sc.doe.gov/production/henp/np/projects/RIA.html

### rp-process

X-ray bursts are the most common thermonuclear explosions in nature. They occur on the surface of accreting neutron stars. Repeated bursts of x-rays are observed in which a given burst lasts for about ten seconds. The repetition time for the bursts can be hours to days. The bursts result from the thermonuclear ap-process followed by rp-process burning. The ignition of each new burst takes place in, and by, the ashes of the previous burst. The shape and magnitude of the resulting light curve is sensitive to details of the properties of the proton-rich nuclei involved. The position of the peaks in the resulting isotope abundance patterns depends on the ashes present at ignition, and so several bursts must be averaged to get an accurate prediction of the nucleosynthesis.

The most important nuclear physics determining the shape and magnitude of observed bursts are the branch point waiting nuclei. For these nuclei the masses and beta-decay lifetimes are needed. In addition, if beta-decay at a waiting point takes place through an excited state, the effective lifetime of the nucleus changes. Because many of the waiting points are N=Z nuclei along the proton dripline, they are expected to exhibit shape isomers (first excited 0+ states), and knowledge of the excitation energy and beta-decay of these isomers is crucial in predicting the light curves. In some cases, there is the possibility that (2p, $\gamma$) may become competitive, and these reaction rates are also of key interest.

### r-process

The site of the r-process is not known but is most likely Type 2 supernovae or merging neutron stars. The details of the shape of the nucleosynthesis pattern can provide the constraints to fingerprint the site. To confirm this, the nuclear physics, particularly of the waiting point nuclei and nuclei along the neutron dripline, is needed. RIA provides the opportunity to measure lifetimes and masses of these nuclei.

At the magic neutron numbers the predicted r-process abundances are very sensitive to the shell structure and shell gaps. This is because the neutron separation energies sensitively affect the neutron capture rates. As discussed earlier, the possible quenching of shell gaps is directly related to the strength of the spin-orbit interaction. Calculations on gap quenching are restricted to two-body nuclear interactions, and the inclusion of the three-body interaction is expected to yield new perspectives.

There is also a need for measurements of the (n, $\gamma$) capture rates for these nuclei and for the waiting point nuclei for the s-process. In the absence of an RIA neutron facility there is suggestion of using surrogate reactions such as the (d, p) reaction. However, for astrophysical needs the neutron capture cross-sections are needed in the 10s of keV neutron energy range. At these low energies, the nuclear theory needed to go from the cross-section of the surrogate reaction to the neutron capture reaction becomes very uncertain, and it is not clear that the technique will be viable. An RIA facility at LANSCE will be a huge advantage for researching neutron-induced reactions. In addition to the astrophysics interests in neutron induced reactions, there are a number of cross sections measurements on unstable nuclei of key interest to the Stockpile Stewardship Program, and for Homeland Security, that become possible with a combined RIA and neutron facility.

## PHYSICS BEYOND THE STANDARD MODEL AT RIA

Despite the remarkable success of the Standard Model (SM), for many theoretical reasons, and especially because of the large number of undetermined parameters of the model, the existence of new physics is expected. The first strong experimental evidence, in the form of neutrino oscillations, suggests some extension of the SM is required. (Without some new source of charge conjugation and parity violation {CPV} the baryon asymmetry of the universe cannot be generated.)

Nuclear and atomic physics make important contributions searching for physics beyond the SM, setting stringent limits on possible new interactions. RIA may provide new opportunities for improving these limits (or to the discovery of new physics). The fields of physics beyond the SM to most likely benefit from RIA include:

- Atomic Parity Violation
- Atomic Electric Dipole Moments
- Nuclear Beta Decay

### Atomic Parity Violation

Experimental investigations of parity violation in atoms probe new electron-quark interactions. In the SM there is such an interaction, mediated by the exchange of the Z-boson. New electron-quark interactions are present in many extensions of the SM. The dominant parity violating effect in atomic transitions is described by the "weak charge", (QW), of the nucleus. The QW contains the dependence of the effect on the coupling constants of the electron-quark interaction. Heavy atoms are favored for experiments, since the parity-violating effect is proportional to ($Z^2$)N.

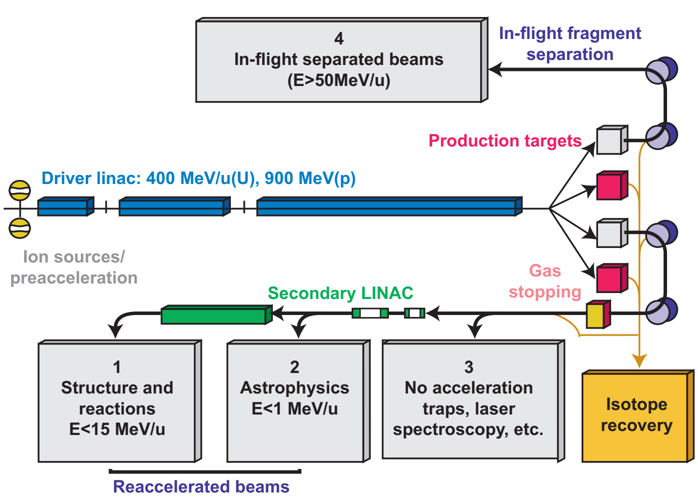
The most accurate measurement of QW is performed in cesium. The calculation for cesium is also the most detailed and accurate. The experimental error and the theoretical uncertainties are comparable in size; both about 0.5%. Theory and experiment agree within one standard deviation. Comparison of the experimental result in cesium with the SM prediction yields an upper limit of a few times $10^{-3}$GF on the strength of a possible new electron-quark interaction. One of the candidates for improving the existing result is francium (Fr). The QW(Fr) is larger than the QW(Cs) by a factor of eighteen. Thus, if an experiment could be carried out in francium with the same precision as in cesium, and the theoretical uncertainties could be controlled at the same level, the limit on the strength of a new electron-quark interaction could be improved by an order of magnitude.

A measurement of the QW(Fr) (which has no stable isotopes) is being attempted at the Stony Brook LINAC. Improved experiments are conceivable at RIA.

## Atomic Electric Dipole Moments

The charge conjugation and parity violation is seen in the decays of the neutral K- and B-mesons. Although the observed effects are accounted for by the Cabibo-Kobayashi-Maskawa phase dKM, the existence of new sources of CPV remains a major question. New charge conjugation and parity violation interactions are present in many extensions of the Standard Model.

The most suitable observables to probe the existence of new CPV interactions are those for which the contribution from dKM is small. Among such observables are the electric dipole moments (EDM) of atoms.




**General layout of the proposed Rare Isotope Accelerator facility.**

The most precise measurement of an atomic EDM in a paramagnetic atom is obtained in $^{205}$Tl, and in a diamagnetic atom in $^{199}$Hg. The EDM of thalium provides the best limit on CPV electron-nucleon interactions, and the EDM of mercury gives the best limit on some of the types of CPV quark and gluonic interactions.

Nuclei with octupole deformation have extra-large enhancements of their Schiff moments, and could help to improve the existing limits on CPV in the non-leptonic interactions. One of the candidates is $^{225}$Ra.

Calculations indicate an experimental limit for the EDM of radium comparable to the present limit on the EDM of mercury will improve the sensitivity to CPV interactions by two to three orders-of-magnitude. An experiment searching for the EDM of radium is under development at Argonne National Laboratory (ANL). A similar enhancement is predicted for the EDM of radon. This enhancement will be searched for at the Tri-University Meson Facility in Canada (TRIUMF). The above EDM experiments could be improved at RIA.

## Nuclear Beta Decay

The ft-values of $0^+ \rightarrow 0^-$ Fermi beta decays provide the most precise value of *Vud*-element of the Cabibo-Kobayashi-Maskawa matrix (CKM). Combined with information on the us- and ub- elements, it is possible to test the unitarity of CKM. Violation of the unitarity relation is evidence for physics beyond the SM; in the form of a fourth quark generation or a new interaction. With the value of *Vud* obtained from a new comprehensive analysis by Hardy and Towner, the test of unitarity fails by 2.4 standard deviations. A possible source of the discrepancy is the value of *Vus*, as indicated by the value obtained in a new measurement. The largest uncertainty in *Vud* comes from the nucleus-independent radiative corrections. The source of the next largest contribution to the error is the isospin breaking corrections. It may be possible to reduce this uncertainty by gaining stronger confidence in the required calculations through improve the accuracy of the available experimental ft-values, and by measuring the ft-values of additional nuclei. For the latter, RIA may provide new opportunities.

In beta decay it is possible to probe for new charged current interactions through measurements of various correlations in the decay probability. In the SM the $d \rightarrow u + e^- + Ve$ transition has a V-A structure. In many extensions of the Standard Model, V + A, scalar- and tensor-type interactions are present. The RIA may provide new opportunities for experimental studies here.

# Appendix F: Additional Capabilities and Opportunities in Nuclear Science with Antiprotons

## ANTIPROTON PRODUCTION AT LANSCE

### Introduction

Beams of protons and heavy ions are used worldwide as efficient treatment modalities for specific forms of cancer near sensitive structures in the human body. Protons and heavy ions work as a result of the inverse dose profile, Bragg-Peak, compared to x-rays, and the enhanced biological efficiency of the energy deposition near the Bragg-Peak, especially for carbon ions.

Antiprotons might also further enhance tumor treatments. Using antiprotons, the combination of additional energy deposition in the Bragg-Peak, due to 1) the annihilation of antiprotons at the end of range, 2) the enhanced biological efficiency of the energy deposition (production of heavy fragments and recoils with short range), and 3) the additional advantage of real time imaging using minimum ionizing particles emanating from the annihilation region, may prove therapeutic.

LANSCE initiated preliminary experiments studying the biological effects of antiproton and proton beams using live cells from standard cell lines at the antiproton decelerator at the European Organization for Nuclear Research (CERN). Results of these tests are very promising and a research program is under development to bring antiprotons to the field of cancer treatments within the next ten years.

Antiproton research demands the highest intensity antiproton source possible. A high-intensity antiproton source will be the prime driver in antiproton production intensities adequate for realistic treatment situations, and open up new R&D opportunities in applied antiproton physics.

### Antiproton Cancer Therapy and Other Applications of Low Energy Antiproton Beams

Comparisons using beams of protons and antiprotons with similar characteristics show significant enhancements in the therapeutic ratio, for example the ratio of damage to the tumor compared with the damage in overlying healthy tissue. Initial studies of peripheral damage due to medium range annihilation products indicate peripheral damage is not a serious problem. The first demonstration experiments on real time imaging of the annihilation event in the target have been performed. These experiments provide the motivation to continue, and much experimentation is necessary before results are put into medical practice.

Current experiments are performed *in vitro*, using cell lines of known reaction to ionizing radiation. To advance research an increase in sample size and target volume, and eventually i*n vivo* experiments, are required. Higher beam intensities are necessary. Therefore, building upon the research at CERN, LANSCE initiated further study of a high-intensity, low-energy (50 – 250 MeV) antiproton source. A cornerstone of this facility would be a proton synchrotron capable of providing pulses of > 1 x $10^{13}$ protons/pulse at energies of >20 GeV.

A short (50 ns) beam pulse of the above specifications will be extracted from the main accelerator roughly every five seconds and focused onto a production target. One technological challenge is improving target technology by increasing the maximum amount of power hitting the target per unit time.

Antiproton production can also benefit a number of other R&D activities; using muon production from intense antiproton pulses for remote sensing, and research towards improving production and storage of antimatter for possible space propulsion applications. Additional applications in materials science and remote imaging are also envisioned.

Several concepts are reported identifying unique applications for low energy antiprotons. Currently, three companies exist in the U.S. that are commercializing the use of antiprotons. Detection of special nuclear material for Homeland Security is proposed. The National Aeronautics and Space Administration (NASA) is currently supporting research into potential propulsion technologies using antiprotons and built the world's largest capacity Penning Trap to hold antiprotons.

If portable traps with long lifetimes prove reliable, universities throughout the country will benefit from a source of antiprotons available for basic studies. Antiprotons react with normal matter to produce neutrons, pions, and gamma-rays with energies between one and 500 MeV. Thus, a trap of antiprotons is a unique source of radiation. For example, antihydrogen formation was demonstrated at CERN and studies in the symmetry of atomic states are planned. Furthermore, the continuing question of gravitational interaction with antimatter could be investigated.

# Appendix G: LANSCE Accelerator Refurbishment and Enhancement Options

## INTRODUCTION

The estimated replacement-cost investment at LANSCE is $1.5 billion dollars.The plan presented below builds on this investment. The possible upgrade options were mapped onto the user-driven requirements, and three possibilities emerged as giving the most scientific impact for the least investment. The one major constraint imposed was that the scheduled beam availability be minimally impacted.

LANSCE-R consists of upgrading and replacing those systems that are at end-of-life so that the existing accelerator can operate reliably for the next two decades.

LANSCE enhancement options at 800 MeV consist of a full radio frequency (RF) system upgrade, replacing the remaining RF systems to support operations at the present repetition rate, but with a maximum pulse length of 2 ms compared to the typical 0.625 ms, and peak currents of 21 mA instead of the existing 17 mA. This extends the performance of the LANSCE linear accelerator (LINAC), and the longer pulse length results in a new maximum duty factor, limited by the water-cooling capacity of the LINAC structure. The 21 mA maximum current is limited by the peak radio frequency power of the existing tubes. This doubles the beam power of the LINAC at a minimal cost, and increases the future capability of LANSCE for future missions.

LANSCE enhancement options also offer the potential for construction of a 20 GeV ring for proton radiography (pRad). The goal is to give a new hydro-test capability that provides radiographs with better spatial resolution, several times better position resolution, a factor of ten to 100 times higher effective dose, and at least ten time frames.

Another potential enhancement entails replacing either part of, or all of, the existing 805 MHz coupled-cavity (CCL) LINAC with superconducting LINAC sections to attain a final beam energy of 3 GeV. High-frequency superconducting (SC) structures can have much higher real-estate gradients (>10 MeV/m) than room temperature (RT) structures (the present CCL is ~ 1 MeV/m). By replacing sections of the RT-LINAC with SC-LINAC sections in the same tunnel allows a significant increase in the final beam energy without the addition of new tunnel. Several options exist for installing the superconducting LINAC while ensuring LANSCE's continued operation, but further studies are required to determine an optional choice that allows for each SC section to be installed and commissioned during scheduled maintenance shutdowns. A variation of this enhancement is described at the end of the SC upgrade section that covers the possibility of replacing the entire 805 MHz LINAC with SC structures. This option also enables increased performance from the pRad ring. Because the initial injection energy of the ring will be raised from 800 MeV to 3 GeV, *ten times the charge can be extracted from the ring*. This allows for improving the signal-to-noise ratio due to the higher charge per pulse, and for producing enough charge for a second axis view at the target station.

A short segment at the end of this section on accelerator upgrades describes a new facility for generating muon beams for several important, new applications.

A summary of the performance improvements and estimated costs is given in Table 1.

## THE LANSCE REFURBISHMENT PROJECT (LANSCE-R)

The first protons were accelerated by the LANSCE-LINAC in June of 1972. Since that time, the mission has evolved, but the physical infrastructure has never been funded at a level to keep pace with evolving standards for operation of such facilities and to maintain acceptable reliability. To correct some of these problems, the National Nuclear Security Administration (NNSA) has invested in selective improvements through the Facility Infrastructure and Refurbishment Project (FIRP). Those efforts have been essential to LANSCE operations, but additional investment is needed. The LANSCE Refurbishment Project (LANSCE-R) will meet operational reliability requirements for the next two decades.[2]

### Technical and Programmatic Objectives

The following is a list of requirements to meet the needs of LANSCE sponsors and users.

The primary requirement—to enable the facility to deliver six to eight months (approximately 4000 – 5000 hours, depending on operating budget) of beam to user programs each year, with no single-point failures that would result in an extended loss of operating capability for any one area during a run cycle.

Achieving this requires the following investments and activities:

- Maintain high-reliability of 805 MHz RF system by using new and modern equivalents of transmitters, high-voltage power systems, ancillary hardware, and buying spare klystrons.

[1]LANSCE User Facility Cost Estimate, Roberts, J. A., Los Alamos National Laboratory, LA-UR-01-4937, 2001.

[2]Proposed Line Item LANSCE Refurbishment Project, Lisowski, P. W., Los Alamos National Laboratory, LA-UR-04-1350, 2004.

| TABLE 1. LANSCE ACCELERATOR ENHANCEMENT UPGRADE OPTIONS, PARAMETERS, AND ESTIMATED COSTS | | | | |
|---|---|---|---|---|
| **Investment** | **Scope** | **Parameter** | **Performance Specs** | **Estimated Cost** |
| LANSCE-R | 800 MeV, 17 mA<br>$H^+$, $H^-$ | Pulse Format for LPSS and MTS<br><br>NxGens Beam Power<br>MTS Beam Power[1]<br>LPSS FOM[2]<br>MTS FOM | 0.625 ms @ 70 Hz<br><br>0.1 MW<br>0.6 MW<br>8.5 kJ/pulse @ 20 Hz<br>0.7 x $10^{15}$ n/cm$^2$/s | $165 to $238M |
| LANSCE Enhancements @ 800 MeV | Full RF System Upgrade<br><br>800 MeV, 21 mA<br>$H^+$, $H^-$ | Pulse Format for LPSS/MTS<br>Additonal pulses for MTS only<br>LPSS Beam Power<br>MTS Beam Power[3]<br>LPSS FOM<br>MTS FOM | 2 ms @ 20 Hz<br>0.625 ms @ 60 Hz<br>0.7 MW<br>1.8 MW<br>33.6 kJ/pulse @ 20 Hz<br>1.5 x 10 $^{15}$ n/cm$^2$/s | $53M to $68M |
| LANSCE Enhancements @ 20 GeV | Synchrotron<br>0.5 Hz, 10 pulses<br>20 GeV $H^-$<br>800 MeV Injection | Protons/Pulse | 5 x $10^{11}$<br>(7 x $10^{12}$ with 3 GeV injection) | ≥$220M |
| LANSCE Enhancements @ 3 GeV | Superconducting LINAC[4]<br>3 GeV, $H^+$, $H^-$ | Pulse Format for LPSS and MTS<br>LPSS Beam Power<br>MTS Beam Power[1]<br>LPSS FOM<br>MTS FOM | 2 ms @ 20 Hz & 1.25 ms @ 30 Hz<br>2.5 MW<br>4.9 MW<br>126 kJ/pulse<br>5.2 x $10^{15}$ n/cm$^2$/s | ~$281M<br>(~$305M)[5] |
| | Muon LINAC | | ~$10^6$ muon | ~$25M |

[1]Assumes a common MTS/LPSS target so the MTS receives the full beam power including the long pulse spallation source (LPSS) power.
[2]FOM = Figure-of-Merit
[3]The total MTS power is set by the 12% duty factor determined by the Drift Tube LINAC (DTL) cooling limitations.
[4]These parameters and costs are for a SC upgrade that replaces the >500 MeV section of the 805 MHz LINAC. The cost to replace the <100 MeV section of LANSCE is estimated to be an additional $80 million.
[5]Assumes replacing the whole RT-LINAC with a SC-LINAC and reusing the RF upgrades from LANSCE-R.

- Maintain and improve the reliability of the 201 MHz RF system by replacing the power amplifiers, intermediate power amplifiers (IPA), and ancillary hardware with modern systems.
- Replace antiquated hardware and software in the accelerator controls, data acquisition, and timing systems that are becoming virtually non-maintainable because of obsolescence.
- Substantially reduce the increasing amount of beam downtime, contributed to by failures in the vacuum and cooling systems for the accelerator and beam-transfer lines.
- Maintain reliability and provide much needed beam-tuning capabilities by refurbishments and additions to the beam-diagnostics systems.
- Remove the single-point Target Moderator Reflector System (TMRS) failure point for the Lujan Center by designing and fabricating a spare.
- Replace or refurbish conventional facilities, including electrical power distribution, heating, ventillating and air conditioning (HVAC) systems, and structures for which unreliability, lack of maintainability, wear-out, or code-compliance issues impact beam availability and/or cost of operation.

## LANSCE ENHANCEMENTS

### Achieving Full Capability at 800 MeV

The simplest and most straightforward improvement to LANSCE is to extend LANSCE modifications to improve the present LINAC capabilities by modifying all of the RF systems to support 2 ms operation, to refurbish the ion sources to allow for higher peak current operation for both the $H^+$ and $H^-$ sources, and to improve beam transport.

Although the LANSCE accelerator can operate at many different repetition rates, the maximum repetition rate is 120 Hz. LANSCE will take full advantage of this maximum repetition rate to provide beam to different facilities.

The RF system requires modification to provide an increase in the peak RF power to accelerate a 21 mA beam and to accommodate a 2.4 percent increase in the RF duty factor. This allows increasing the pulse length for the 20 Hz pulses to 2 ms. Primarily the internal structures in a klystron and the cooling of these structures is set by the maximum pulse length and not the integrated duty factor so even though the duty factor increase for the RF is small, the klystron design is impacted. Allowing for RF rise and settling time in the cavities, this will increase the maximum RF pulse to approximately 2.3 ms.

The newer klystrons have an improved efficiency of sixty-five percent as compared to the existing tube efficiency of forty percent. *This saves approximately $1 million dollars per year in electricity costs if LANSCE operates 4000 hours per year,* based on an electricity charge of $0.07/kWhr.

Assuming the LANSCE-R project is implemented, the additional cost for the complete replacement of the 805 MHz RF and high voltage (HV) required to support the 21 mA operation and the duty factor increase is estimated at $43 million, plus an additional $2 million to upgrade the 201 MHz, giving a cost estimate of $45 million—thus, with a thirty percent contingency, the total additional cost is $60 million.

The estimated cost for klystron modifications to provide for a higher peak current from the ion sources is $6 million. Thus, the integrated contingency cost estimate for upgrading the RF and ion sources is $66 million.

## 20 GeV pRad Ring

In this section estimated costs, schedules, and capabilities are presented for a 20 GeV slow-cycling proton synchrotron machine at LANSCE. The goal of this upgrade is to provide a new hydro-test capability that gives radiographs with better spatial resolution at a lower dose than existing capabilities, several times better position resolution, a factor of ten to 100 times higher effective dose, and up to ten time frames.

The choice of 20 GeV is driven by the classified results of static experiments performed using 24 GeV/c and 7.5 GeV/c beams from the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory. These experiments showed that a 20 GeV beam energy is sufficient for measuring weapons physics processes in scaled experiments that are important for certification and is suitable for full-scale hydro-testing on the largest stockpiled systems, with significantly enhanced physics returns. The requirements for this machine are derived from a combination of the results from the AGS experiments and from requirements studies carried out over the last decade. These requirements are listed in Table 2.

| TABLE 2. pRad MACHINE REQUIREMENTS | |
|---|---|
| Number of pulses | >5 |
| Minimum pulse spacing | ~200 ns |
| Protons per pulse | $5 \times 10^{11}$ |
| Time format | Individual pulse extraction |

The 800 MeV LANSCE-LINAC can be used as an injector, saving the time and money it would take to build and commission a separate injector LINAC. In addition, the existing infrastructure of trained personnel and equipment simplifies commissioning the synchrotron ring.

The number of proton pulses (snapshots in time) is driven by the need to measure density as a function of time. Five pulses spaced at a minimum of 200 ns are sufficient. Up to ten pulses can be used for the 20 GeV ring presented here, limited by the circumference of the synchrotron. The proton dose, proportional to the number of protons per pulse, in Table 2 is twice what was used in validation experiments described below.

Considerable benefit can be gained by the use of an achromat lens (not presently implemented) in conjunction with proton radiography. Coulomb scattering of the proton beam in a target leads to chromatic aberrations in images that result in a degradation of the radiographic resolution. The use of an achromat lens effectively removes the chromatic aberration, restoring resolution. While there are software techniques that can be brought to bear to also remove these aberrations to some degree, prudent experimental practice suggests the simultaneous use of both hardware and software methods. Calculations show that for objects of relevant areal densities (g/cm$^2$), significantly improved resolution can be obtained with an achromat lens for energies as low as 3 GeV. Although these estimates do not include all known sources of error, the scaling of the resolution with energy clearly indicates the value of implementing an achromatic lens.

## pRad Ring Cost

The 20 GeV proton synchrotron proposed here is well within the parameters of other accelerator projects that have been proposed and/or built. The reported (or estimated) costs of these accelerators vary considerably from site to site; nevertheless, we can make a reasonable estimate, accurate to probably twenty-percent.

The costs of several synchrotron projects were studied in the Advanced Hydro-Test Facility (AHF) project. Those costs were summarized and incorporated into a model for costing synchrotrons. Basically, the model uses gross measures, such as total weight of dipole and quad magnets, total amount of direct current (DC) power, total length of beam pipe, etc. We applied cost rates to generate a total equipment cost and factors for overheads, design costs, and contingency, to arrive at the Total Project Cost (TPC) for the accelerator equipment. A similar breakdown was performed for the Balance of Plant (BOP) and applied cost-loading factors specific to the civil construction process. The result of the two exercises is an estimated TPC.

The information in Table 3 is based on the present design of the 20 GeV ring. In addition, LANSCE created a rough design for the magnets, giving the overall parameters for the dipoles and quads: total weight, water flow, power requirements, and so forth. The costs (in Table 3) have not been externally reviewed and thus serve only as a rough estimate.

## The LANSCE Site

The synchrotron must be situated at the TA-53 site in a way that it does not interfere with other structures. Figure 1 shows one such placement. In this layout, there are approximately 300 m of transfer lines. The costs of magnets, vacuum, and other equipment are specific to the 300 m length. The length of a standard focusing section is taken to be 15 m, so that twenty quadrupole lenses are needed for the 300 m transfer lines.

Costs for septa and C-magnets are included in the injection and extraction systems of the synchrotron. Even though Figure 1 shows that the beam bends in the transfer lines, no cost for dipoles is included in the estimate. This is because the layout shown is not the definitive layout, and an optimization would probably result in less bending than shown in the figure. Any net bending that remains after such an optimization will come out of the contingency. Also, because the beam goes through the transfer lines only once, the vacuum requirements are considerably relaxed. Thus the cost-per-meter of the vacuum system is lower than for the synchrotron.

The estimated facility capital cost is given in Table 4. For the civil construction (BOP) costs, only the tunnel cost and some power-related costs are scaled.

In summary, the estimated cost for a pRad ring is approximately $220 million.

As an alternative approach, a 6 GeV rapid cycling synchrotron (RCS) that can also produce 20 GeV pulses for pRad was reviewed. The total cost was estimated to be $550 million. Since a RCS is at least as expensive as building a separate superconducting (SC) LINAC and pRad ring, an RCS was no longer considered.

**TABLE 3. COST ESTIMATE FOR THE TECHNICAL EQUIPMENT IN THE 20 GeV RING**

| Main Ring | Qty | Unit | Rate ($K) | Extended $M |
|---|---|---|---|---|
| Dipoles | 448 | tons | 13 | 5.8 |
| Quads | 456 | tons | 20 | 9.1 |
| DC Power | 2 | MW | 350 | 0.7 |
| Correctors | 10,000,000 | M | 0.0001 | 1.0 |
| RF Power | 0.024 | MW | 3200 | 0.1 |
| RF Cavity | 1 | ea | 1000 | 1.0 |
| Vacuum | 108 | m | 5 | 3.0 |
| Extraction Sys. | 1 | ea | 3500 | 3.5 |
| Injection | 1 | ea | 2200 | 2.3 |
| Diagnostics | 152 | dev | 16 | 2.4 |
| Controls | 760 | pts | 1.2 | 0.9 |
| Cable | 608 | m | 2 | 1.2 |
| Utilities | 608 | m | 2 | 1.2 |
| Subtotal | | | | 32.2 |
| | Misc. Sys. | 5% | | 33.8 |
| | Load | 26% | | 42.6 |
| | Design | 30% | | 55.4 |
| | Contingency | 40% | | 77.5 |
| Total (Including Proj. Mgmt.) | | 7% | | 83.0 |

## UPGRADE OF EXISTING ROOM TEMPERATURE (RT) LINAC WITH A 3 GeV SUPERCONDUCTING LINAC

This proposed upgrade would increase the energy of the LANSCE-LINAC from 0.8 GeV to 3.0 GeV using state-of-the-art SC technology, while maintaining a multi-user capability, minimizing disruption to LANSCE operations, and giving a significant increased operational capability for pRad by improving the resolution. The increased performance for pRad can be for an increase factor of ten in protons per pulse, or provide enough protons for a second viewing axis.

A superconducting LINAC provides an average rate of energy gain that is ten times that of the present LANSCE-LINAC. It is based on proven RF superconducting technology developed for the TESLA electron-positron project (Figure 2). The upgrade would be installed and commissioned during the scheduled beam shutdowns, thus allowing LANSCE operations to continue with minimal impact from the upgrade. The upgraded LINAC could accelerate the peak current of 21 mA and a 2 ms pulse length to 3 GeV. The upgraded LINAC would deliver a total beam power of up to 5 MW.

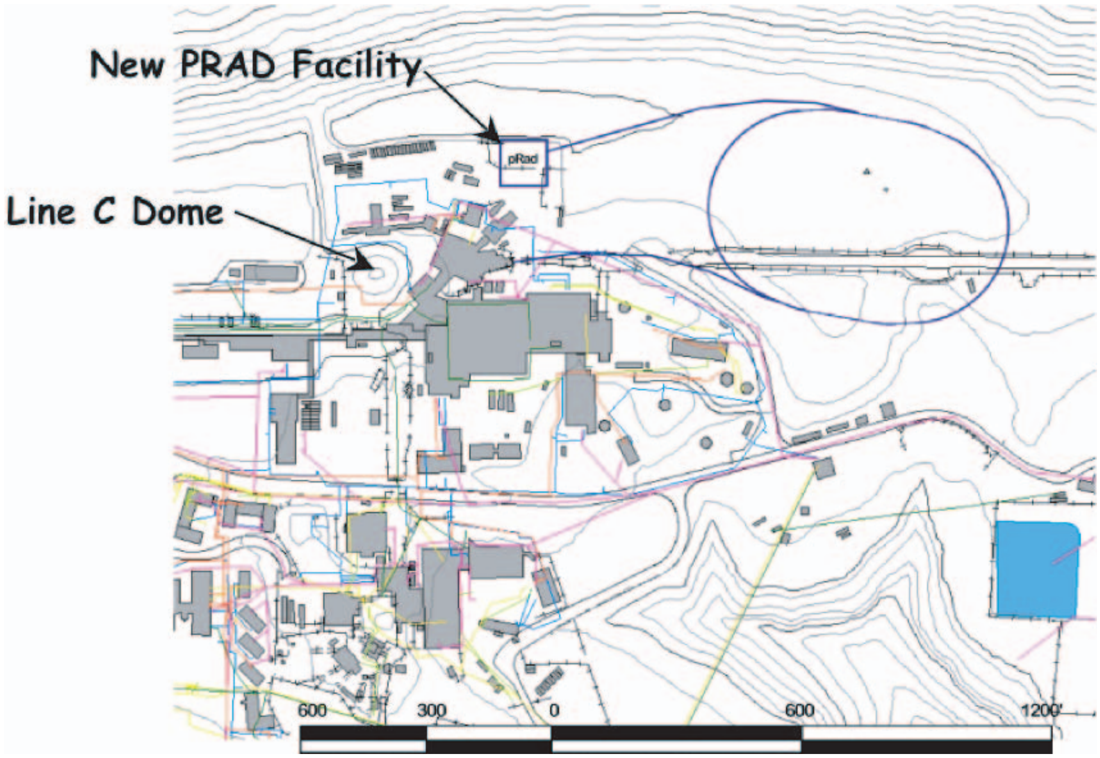



**FIGURE 1.** A possible site for the 20 GeV ring, shown overlaid on the LANL TA-53 site.

| TABLE 4. SUMMARY OF COSTS FOR THE 20 GeV RING. COSTS ARE IN $M, FY05 | |
|---|---|
| Main Ring | $83 |
| Transfer Lines | $7 |
| Firing Site & Detectors | $17 |
| Achromat | $20 |
| Balance of Plant | $93 |
| **Total** | **$220** |

## SUPERCONDUCTING LINAC CONCEPT

### LINAC Upgrade to 3 GeV

The new LINAC would be installed in the existing LANSCE tunnel with a carefully phased installation to replace sections of the present coupled-cavity LINAC (CCL). If tunnel space allows, installation could be alongside the existing LANSCE-LINAC, to decrease risk. The upgrade would be installed and commissioned during the scheduled beam shutdowns, thus allowing LANSCE operations to continue with minimal impact

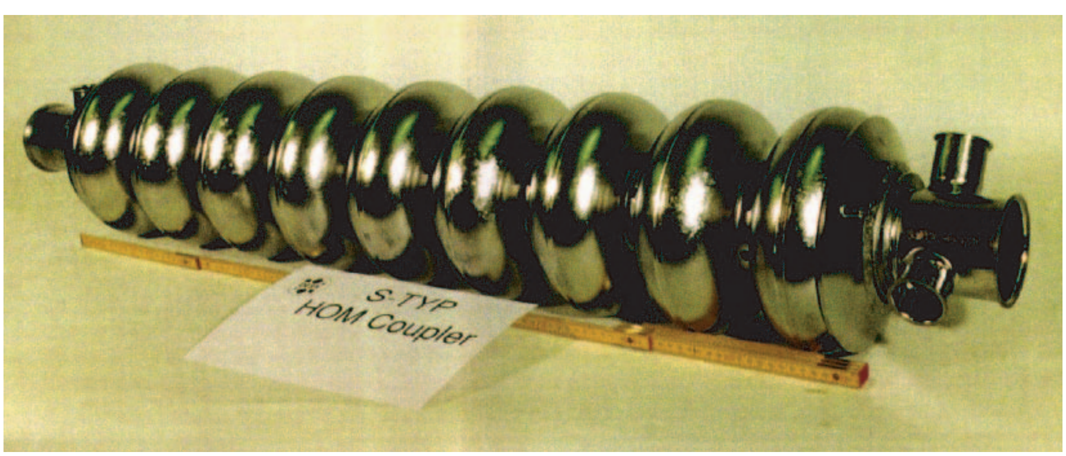



**FIGURE 2.** TESLA nine-cell 1300 MHz elliptical superconducting niobium accelerating cavity used for acceleration of relativistic electrons. The design velocity in LANSCE's first iteration is $\beta = 0.85$ times the speed of light.

from the upgrade. Here we assume a peak current of 21 mA and a pulse length of 2 ms with a repetition rate of 20 Hz for the NxGens long pulse spallation source. The MTS targets would receive 0.625 ms pulses at 60 Hz. It is assumed that both the MTS and NxGens can run simultaneously. Adding in the PSR and Isotope Production Faciity (IPF) at 20 Hz and 0.625 ms each uses up the available duty factor for the Drift Tube LINAC (DTL) structure. Figures-of-merit relevant to the LPSS and MTS are shown in Table 4 for these assumed pulse figures at both 800 MeV and 3 GeV.

**TABLE 4. FIGURES-OF-MERIT FOR THE 800 MeV and 3 GeV UPGRADES**

| Beam Energy | Avg. NxGens Beam Power (MW) | NxGens kJ/pulse | Avg. MTS Beam Power (MW) | MTS Neutron Flux n/sec/cm$^2$ |
|---|---|---|---|---|
| 800 MeV | 0.7 | 34 | 0.6 | 0.8 x $10^{15}$ |
| 3 GeV | 2.5 | 126 | 2.4 | 2.9 x $10^{15}$ |

It is essential that any upgrade scheme not preclude present operations, i.e., 800 MeV $H^-$ beam directed by the switchyard to the existing PSR.

Two scenarios are considered:

1) A minimal replacement scenario in which as much of the present CCL is retained so that 3 GeV can be attained in the present LINAC tunnel.

2) Complete replacement of the CCL with a SC-LINAC. This option minimizes operating-power costs and is consistent with possible future high-current upgrades.

Figure 3 shows the two scenarios to correct longitudinal scale. The present LINAC and the tunnel (to ten times transverse scale) are shown in the center of the drawing. The transport lines and their lengths are also shown.

## Transport Considerations

Irrespective of the LINAC configuration, $H^-$ beam must be available at 800 MeV for PSR, Weapons Neutron Research

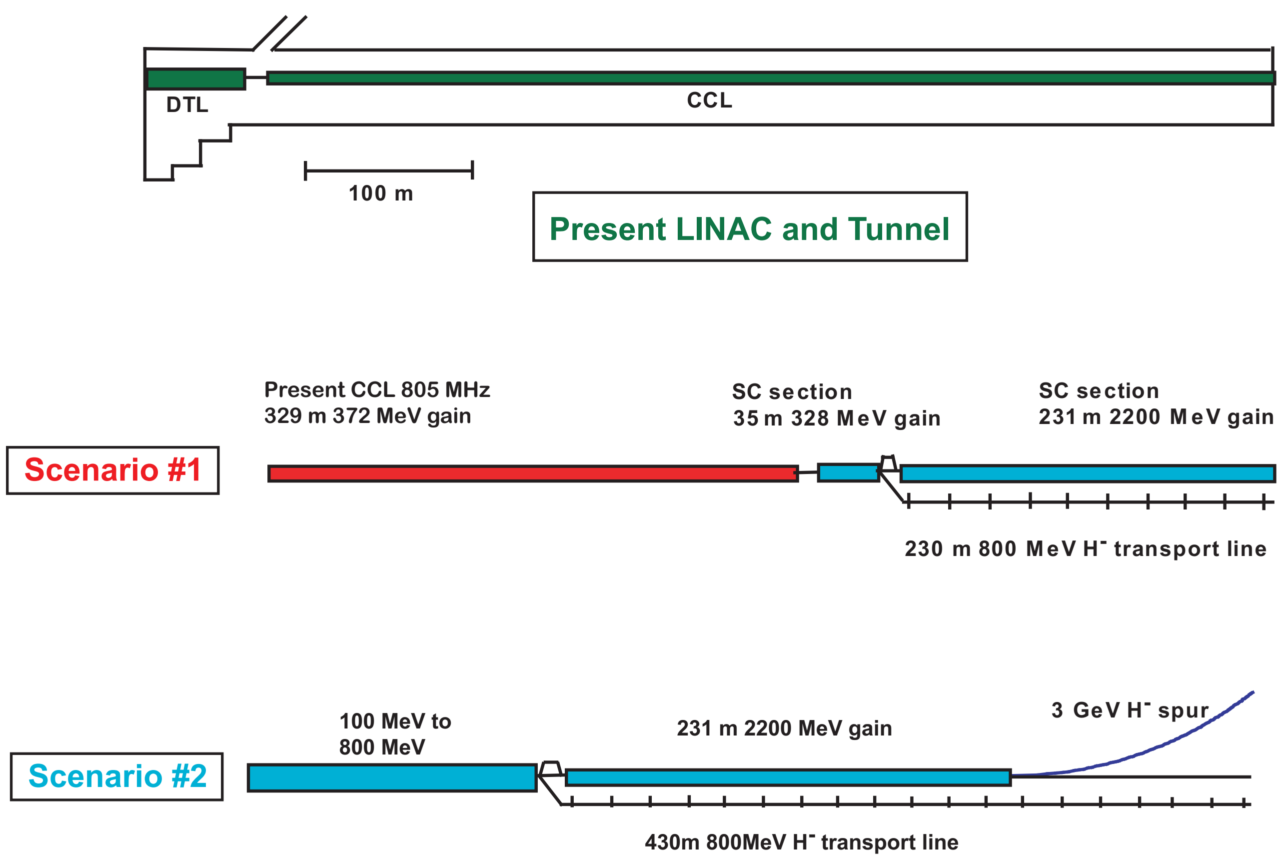



**FIGURE 3**. The two LINAC scenarios discussed along with the present LINAC. The horizontal scale is correct with the vertical scale for the tunnel greater by a factor of ten. Transverse widths of the LINAC structures are approximate.

(WNR), and operations in line X/C. This is readily accomplished by dividing the LINAC into two sections with the split at 800 MeV. At the split, a pulsed dipole (rise time < 8.3 ms), and normally switched on, deflects the 800 MeV $H^-$ beam into a transport line (shown in Figure 1) leading to the present switchyard. The $H^+$ beam, destined for Area A, will be injected into the remainder of the SC-LINAC through an achromatic chicane and be accelerated to 3 GeV. The pulsed dipole is turned off to further accelerate $H^-$ macropulses. The high-energy $H^+$ beam can then be directed over the switchyard in a similar manner to the present scheme. The high-energy $H^-$ beam (for 3 GeV injection into the pRad ring) is routed toward the east to a transport line, with bend radius greater than 87 m to prevent field-stripping losses. Note that such switching is more readily accomplished with the second scenario that leaves substantial space in the LINAC tunnel and preempts switchyard modifications. Since the SC-LINAC cryostat is about 1 m in diameter, there should be adequate room in the tunnel for the 800 MeV transport line.

As a possible alternative to the 800 MeV transport line, both 800 MeV and 3 GeV could be obtained in alternate macropulses by appropriate phasing of the LINAC cavities. Further study will be required to assess the feasibility of adequately focusing a beam of both energies. In this case, the beam may not be matched transversely at both energies unless a fast-matching scheme could be implemented. Subsequent betatron oscillations can cause substantial beam loss and reduce beam quality.

### Scenario 1: Minimal Coupled-Cavity LINAC Replacement

An 805 MHz superconducting structure with real-estate energy gradient of 10 MeV/m is added to the end of the truncated LANSCE 805 MHz CCL. Respective structure lengths are adjusted so that an energy of 3 GeV is attained at the tunnel end. The LINAC section lengths and transition energies are given in Figure 3. Upgraded LANSCE-RF systems would be used to power the 805 MHz RT sections and SC sections. Further consideration needs to be given to directing the high-energy beams in appropriate directions, likely requiring changes to the switchyard.

### Scenario 2: Complete Coupled-Cavity LINAC Replacement

The entire CCL is replaced by a superconducting LINAC. First-order considerations require a lower beta 805 MHz structure to accelerate the 201.25 MHz beam from the drift tube LINAC (DTL). A LINAC section similar to the high-beta Spallation Neutron Source at Oak Ridge National Laboratory (SNS) structure with a real-estate energy gradient of 6.6 MeV/m is used up to an energy of 500 MeV. Further acceleration uses an 805 MHz SC structure with real-estate gradient of 10 MeV/m and a break for switching 800 MeV beam.

Since there is substantial room in the tunnel, greater versatility than for Scenario One is allowed in the beam transport. Figure 4 suggests deflection of the high-energy $H^-$ beam through the tunnel walls. Alternatively, both the $H^-$ and $H^+$ beams can be directed over the switchyard and separated before entrance into Area A, without switchyard modification. The 800 MeV $H^-$ beam is transported some 500 m before reaching the switchyard. Off-momentum beam will see a delay of 5.7 ns per percent of momentum deviation with possible consequences for WNR if there are substantial energy tails.

## TECHNICAL DESCRIPTION OF THE LINACS

Both scenarios use (nominal) 805 MHz SC-LINAC sections starting at a beam energy near 500 MeV. Since the ratio of the beam velocity to that of light is $\beta = 0.76$ at 500 MeV and $\beta = 0.97$ at 3.0 GeV, a single type of elliptical cavity with structure $\beta = 0.85$ can be used. At slightly greater expense, the beam velocity can be better matched by varying cavity dimensions in step with the energy.

The proposed cavity is based on previous project development for a similar 1.3 GHz cavity used in the TESLA test facility. This nine-cell cavity has reached reliable operating fields $E_0T$ of over 25 MV/m in a large number of production cryomodules made by industry. The LANSCE superconducting RF structures laboratory in 1992 produced a shorter cavity at 3 GHz with a record gradient of ~40 MV/m. A modest 20 MV/m gradient that can readily produce a real- estate gradient of 10 MV/m is assumed.

A smaller cryomodule (four cavities per cryomodule, as opposed to eight used in the TESLA test facility) with doublet focusing to match the present lattice is proposed. Each cryomodule requires one RF station of 1.8 MW (Figure 4), for the 21 mA beam. Further parameters for the cryomodules and LINAC for a first-order design are given in Table 5 and Table 6 respectively. In Table 6 an 80 Hz repetition rate is assumed. Parameters for either scenario in these tables are nominally the same. The RF system as shown in Figure 4 will utilize one RF station to power four cavities. The low level RF feedback control will be based on the average phase and amplitude error of the four cavities from their desired set points. This will result in high individual cavity field errors when compared to a RF system design where a single klystron is utilized for each SC cavity, but the LINAC is more tolerant to individual cavity errors at the high energies. The RF system cost has a high dependence on the number of RF sources, so the four-way split becomes a cost versus performance trade-off. This four-way power division is

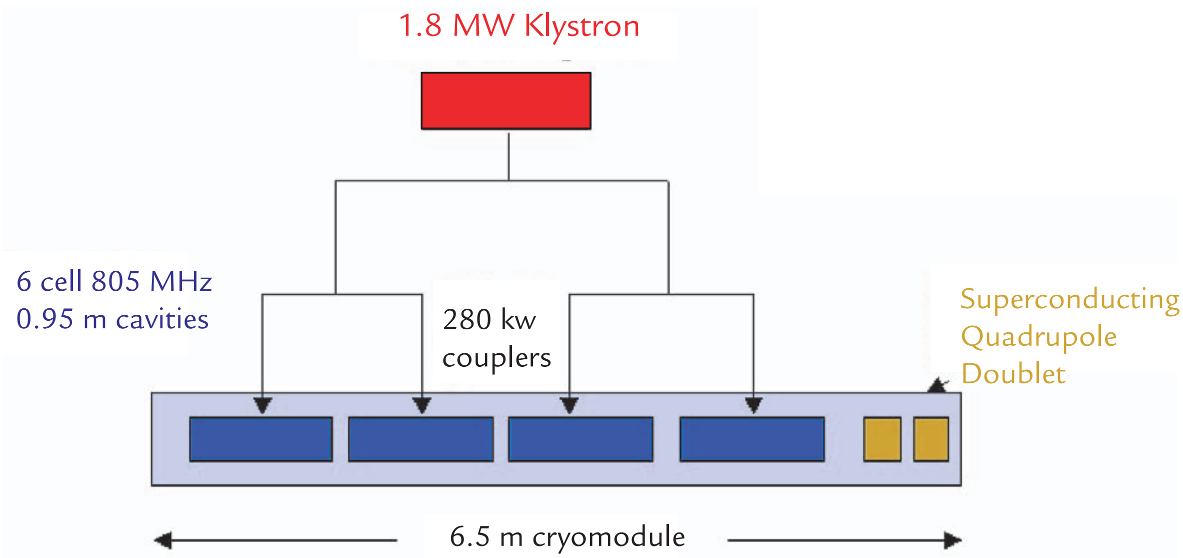



**FIGURE 4.** A block diagram showing a potential cryomodule for the 3.0 GeV upgrade.

similar to what was modeled for LANSCE's accelerator production of tritium (APT) project and was determined to be acceptable. LANSCE will operate two klystrons from a single pulsed DC power supply.

## Scenario 2

In Scenario One a section of the existing 805 MHz RT-LINAC accelerates beam to nearly 500 MeV before further acceleration to 3 GeV by the SC structure described above. In Scenario Two the entire 805 MHz LINAC is replaced, similar in approach to that used in the SNS-LINAC. Further detailed considerations may suggest a more graded approach to the LINAC gradient but first-order considerations suggest the scheme described. LANSCE staff has substantial experience with SC cavities of this frequency, and industry has been successful in producing working cryomodules. LANL has demonstrated 28 MV/m for 805 MHz elliptical cavity fields.

For Scenario Two, Section 1, the lowest-energy section, uses six-cell $\beta = 0.5$ cavities to accelerate the beam from 100 to 185.6 MeV. These cavities are similar to those developed for APT, having similar cavity shapes, but of slightly higher frequency. Section 2 uses cavities identical to the lowest-energy SC-LINAC section for SNS. Table 7 lists some of the parameters for the <500 MeV LINAC. LANSCE assumed a constant energy-gain per cavity based on the average energy-gain per cavity value. Use of the $\beta = 0.61$ cavities up to the higher energy of 500 MeV comes with the penalty of somewhat degraded accelerating efficiency due to a poorer transit-time factor at the higher beam velocity, however, only two types of accelerating cavities are required.

The cryomodule parameters for Section 1 were estimated by scaling parameters from Section 2 by the ratio of the cavity geometric $\beta$ values for the two sections. For Section 1 the cavity accelerating gradient was assumed to be 13 MV/m, the transit-time factor 0.6, and the operating synchronous phase -30°. These parameters give a conservative estimate of the energy gain per cavity for Section 1, whereas the Section 2 parameter values are directly from the SNS parameter list.

For SNS, a single RF generator is used per cavity. The basis for the cost for this RF system is a system where LANSCE splits the power from the klystron four ways and drive four consecutive cavities. LANSCE would exercise high-accuracy low-level RF control (less than .5 percent, .5 degrees cavity-field-amplitude and phase) for the average error between the two cavities, but the individual cavity field error would be higher. Beam-dynamics simulation is required before committing to this approach. The upgraded LANSCE-RF systems would be used. The klystron operating points would be very conservative relative to their design and should result in very reliable operation and long life. For this design LANSCE could run twelve klystrons from a single-pulsed-high-voltage power source.

## COSTS

The cost estimates, shown in Table 8, were derived from the APT, SNS, AHF, and TESLA projects as well as from more recent local assessments. The TESLA analysis of structure costs show a rapidly decreasing structure cost with gradient. The <500 MeV structure costs were derived from actual SNS costs where applicable. The RF costs were based on extrapolation of APT and SNS costs. Cryoplant costs were

**TABLE 5. CAVITY AND CRYOMODULE PARAMETERS FOR SCENARIO 1**

| **Parameter** | |
|---|---|
| RF frequency (MHz) | 805 |
| Cavity design beta | 0.85 |
| Cells per cavity | 6 |
| Nominal accelerating gradient E0T (MV/m) | 20 |
| Real-estate gradient (MeV/m) | 10 |
| Aperture radius (cm) | 6 |
| $Q_0$ | $5 \times 10^9$ |
| $ZT_2/Q_0$ | 500 |
| Active cavity length (m) | 0.95 |
| Number cavities per cryomodule | 4 |
| Cryomodule length (m) | 6.5 |
| Cryomodule period (m) | 7.0 |
| Focusing lattice | Superconducting doublet |
| Number of cryomodules | 37 |
| Number cavities | 148 |
| Total SC-LINAC length (m) | 256 |
| Number of klystrons | 37 |
| Nominal klystron power (MW) | 2 |
| Klystrons per cryomodule | 1 |
| Quadrupoles per cryomodule | 2 |
| Number of quadrupoles | 74 |
| Quadrupole effective (m) | 0.3 |
| Quadrupole gradient (kG/cm) | 1.5 |

**TABLE 6. LINAC PARAMETERS FOR SCENARIO 2**

| Parameter | NxGens 3 GeV SC-LINAC* | MTS | 5 Cryomods, PSR |
|---|---|---|---|
| Rep rate (Hz) | 20 | 60 | 20 |
| Pulse length (ms) | 2 | 0.625 | 0.625 |
| Start energy (MeV) | 500 | 500 | 500 |
| Exit energy (MeV) | 3000 | 3000 | 800 |
| Average beam power on target (MW) | 2.52 | 2.36 | 0.21 |
| Accelerating gradient $E_0T$ (MV/m) | 20 | | |
| Synchronous phase (deg) | -28.65 | | |
| Energy gain per cavity (MeV) | 16.89 | | |
| Peak RF power per cavity (MW) | 0.355 | | |
| Required klystron power (MW)* | 1.92 | | |
| Peak single cavity wallpower loss (W) | 228 | | |
| Operating temperature (deg K) | 2 | | |
| Number of cavities | 148 | 148 | 18 |
| Total cavity dynamic cryogenic load (kW) | 1.55 | 1.87 | 0.08 |
| Static cryogenic load (kW)** | 1.33 | | |
| Distribution cryogenic load (kW) | 0.306 | | |
| Equivalent 4.5K cryogenic load (kW) | 12.62 | 7.41 | 0.30 |
| AC refrigerator power (MW) | 3.72 | 2.19 | 0.09 |
| AC power for RF system (MW) | 5.61 | 5.26 | 0.21 |
| Total AC power (MW) | 9.33 | 7.44 | 0.30 |
| **Net RF AC power (MW)** | | | **11.08** |
| **Net refrigeration AC power (MW)** | | | **6.00** |
| **Net AC power (MW)** | | | **17.08** |

*Quantities listed in the NxGens column but not in others apply to all columns. Extensive quantities are added in a row to obtain totals.

**TABLE 7. SCENARIO 2 SC-LINAC PARAMETERS**

| Parameter | Section 1 | Section 2 |
|---|---|---|
| Output Energy | 185.6 MeV | 500 MeV |
| SC Cavity Type | 6-cell Elliptical | 6-cell Elliptical |
| | 0.5 | 0.61 |
| No. Cavities/Cryomodule | 3 | 3 |
| No. Cryomodules/Section | 8 | 18 |
| Total Cavities/Section | 24 | 54 |
| Cryoperiod Length | 4.786 m | 5.839 m |
| Focusing Lattice Type | Doublet Focusing | Doublet Focusing |
| Active Cavity Length (m) | 0.559 | 0.682 |
| Ave. Energy Gain/Cavity (MeV) | 3.58 | 5.82 |
| Ave. Energy Gain/Cryomodule (MeV) | 10.7 | 17.5 |
| Real-Estate Gradient (MeV/m) | 2.2 | 3.0 |
| Required peak RF Power/cavity (kW) | 75 | 122 |
| AC power for RF system (MW) | 0.55 | 2.00 |
| AC power for cryostat (MW) | 0.35 | 0.67 |
| Section length | 38.3 | 105.1 m |
| **Total Length = 143.4 m** | | |
| **Total AC power = 3.57 MW** | | |

**TABLE 8. COST ESTIMATES FOR TWO OF THE SC UPGRADE PATHS**

| Scenario 1 | | Scenario 2 | |
|---|---|---|---|
| System | Cost M$ | System | Cost M$ |
| Structure | 31 | Structure | 46 |
| RF system | 55 | RF system | 13 |
| Cryoplant | 45 | Cryoplant | 61 |
| Diagnostics & controls | 25 | Diagnostics & controls | 35 |
| Transport & matching | 10 | Matching | 15 |
| R&D | 30 | R&D | 40 |
| Management | 20 | Management | 25 |
| | | | |
| **Total** | **216** | **Total** | **235** |
| add 30% contingency | 281 | add 30% contingency | 305 |

strongly influenced by the AHF work that improved on APT estimates. Labor rates were adjusted in each case to current LANL figures. A conceptual-design needs to be undertaken to accurately assess costs. Substantial R&D should be done to ensure that LINAC replacement is successful, to the point of installing a prototype in the present LINAC beam. Optimization of structure and RF systems can lower costs from this first-order approach.

The cost of replacing the entire CCL with SC structure is estimated to be only ten percent more than a partial replacement. The reuse of the LANSCE-R 805 RF-systems would provide all of the RF power required for an entire 3 GeV SC upgrade. If <500 MeV RT-LINAC is kept, nineteen new RF stations would be required. This cost almost equals the cost of the <500 MeV SC structure and its associated cyroplant.

## Replacement of the LANSCE Front End

To take full advantage of the SC replacement of the CCL requires replacement of the <100 MeV segment of the LINAC. This would significantly improve overall system performance and reliability. This would be done by replacing the ion sources and DTL with two radio frequency quadrupoles (RFQs) and a new DTL structure operating at 402.5 MHz. The estimated cost is $80 million.

## MUON LINAC

LANSCE is the one of the most powerful proton accelerators in the world and can produce high secondary particle fluxes. The installation of an MTS will allow production of muons in Area A. An innovative high-collection source promises to produce muons at low energies with low emittance suitable for further acceleration to produce high intensity (~$10^6$/s). With the University of California, Riverside, LANL is pursuing NSF conceptual-design funding (Figure 5).

Many applications of muon spin resonance can be applied to most materials. This research is complementary to LANSCE work on plutonium aging and the following property measurements: magnetic ordering, surface condition, spatial inhomogenities, superconductivity. This facility can uniquely explore other systems such as hydrogen adsorption, biological systems, microcrystal properties, and chemical analysis on small-scale samples. In addition, high-energy muons are complementary to pRad because muon radiography probes static samples with negligible damage or activation and has high sensitivity to elemental composition. Another application is threat-reduction studies of devices for potential detection of nuclear materials.

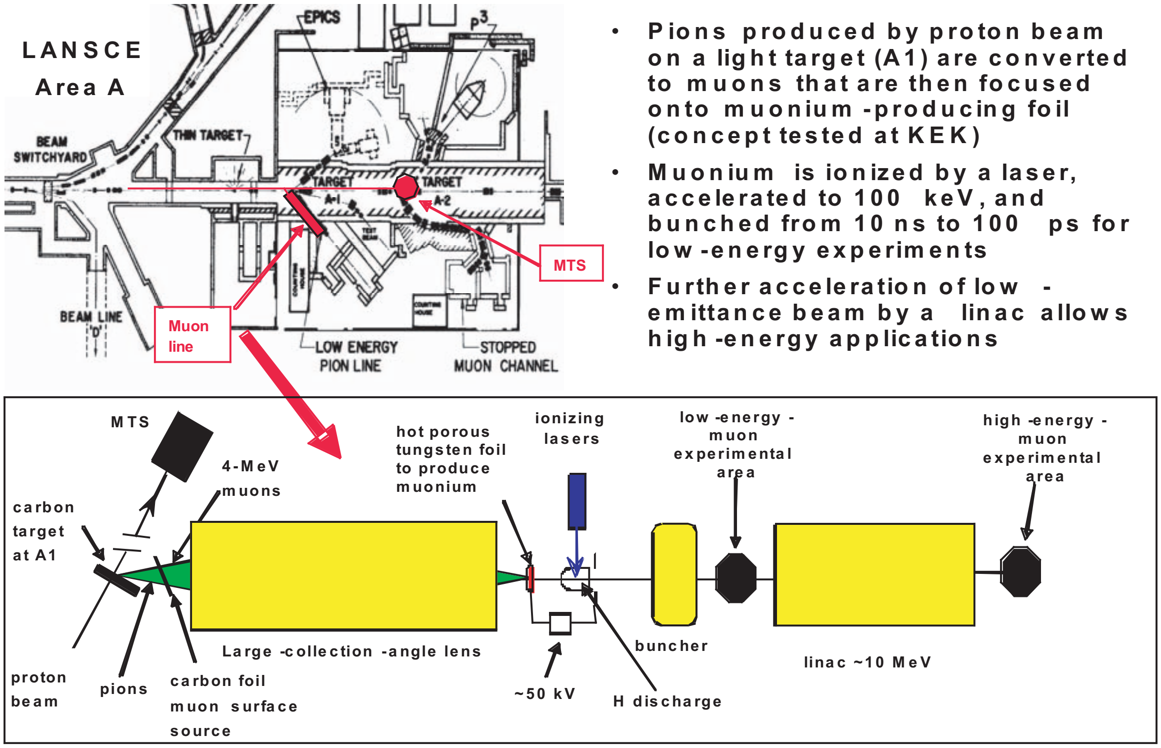



**FIGURE 5**. Schematic of muon source beam lines and construction.

## Appendix H: Abbreviations and Acronyms

| | |
|---|---|
| **AC** | Alternating Current |
| **AFCI** | Advanced Fuel Cycle Initiative |
| **AGS** | Alternating Gradient Synchrotron |
| **AHF** | Advanced Hydro-test Facility |
| **ANL** | Argonne National Laboratory |
| **APS** | American Physical Society |
| **APT** | Accelerator Production Tritium |
| **ASC** | Advanced Simulation Computing program |
| **ATR** | Advanced Test Reactor, Idaho National Engineering and Environmental Laboratory |
| **AWE** | Atomic Weapons Establishment, United Kingdom |
| **BES** | Basic Energy Sciences, Department of Energy |
| **BOP** | Balance of plant |
| **BOR60** | Fast-spectrum Reactor in Russia |
| **BNL** | Brookhaven National Laboratory |
| **CCD** | Charge-coupled Device |
| **CCL** | Couple-cavity LINAC |
| **CERN** | European Organization for Nuclear Research, Geneva, Switzerland |
| **CINT** | Center for Integrated Nanotechnology |
| **CKM** | Value of the Cabibo-Kobayashi-Maskawa Matrix. |
| **CPT** | The combined transformation of charge conjugation, space reversal, and time reversal. |
| **CPV** | Charge Conjugation and Parity Violation |
| **Cs** | Cesium |
| **C-SNS** | Chinese Spallation Neutron Source |
| **DANCE** | Detector for Advanced Neutron Capture Experiments |
| **DARHT** | Dual-Axis Radiographic Hydrodynamics Test |
| **DC** | Direct Current |
| **dpa** | Displacements per Atom |
| **DOE** | Department of Energy |
| **DOS** | Density-of-states |
| **DSH** | Damaged Surface Hydro |
| **DTL** | Drift Tube LINAC |
| **ECAP** | Equal Channel Angular Processing |
| **EDM** | Electric Dipole Moment |
| **EOS** | Equation-of-state |
| **ESS** | European Spallation Source Project |
| **eV** | electron volt |
| **FCC** | Face-centered Cubic |
| **FDS** | Filter Difference Spectrometer |
| **FIGARO** | Fast-Induced Neutron Gamma-Ray Observer |
| **FIRP** | Facility Infrastructure and Refurbishment project |
| **FOM** | Figure-of-merit |
| **Fr** | Francium |
| **GEANIE** | Germanium Array for Neutron-Induced Excitations |
| **Gen-IV** | Generation-IV Advanced Reactor Program |
| **GTL** | Genomes to Life |
| **GPa** | Guga Pascal GeV/c |
| **$H^+$** | Hydrogen Ion |

| | |
|---|---|
| **$H^-$** | Hydrogen Ion |
| **HE** | High-explosives |
| **HFIR** | High Flux Isotope Reactor, ORNL |
| **HV** | High-voltage |
| **HVAC** | Heating, Ventillation, and Air Conditioning |
| **Hz** | Hertz |
| **ILL** | Institut Laue-Langevin in Grenoble, France |
| **IPA** | Intermediate Power Amplifier |
| **IPF** | Isotope Production Facility |
| **ITER** | International Thermonuclear Experimental Reactor |
| **JOYO** | Fast-spectrum reactor in Japan |
| **JPARC** | Japanese Proton Accelerator Research Complex |
| **kJ** | Kilojoule |
| **kWh** | Kilowatt hour |
| **LAMPF** | Los Alamos Meson Physics Facility |
| **LANL** | Los Alamos National Laboratory |
| **LANSCE** | Los Alamos Neutron Science Center |
| **LANSCE-R** | LANSCE Refurbishment |
| **LAPTRON** | Los Alamos Pressure-Temperature Research Online Neutronmeter |
| **LEP** | Lifetime Extension Program |
| **LINAC** | Linear Accelerator |
| **LLNL** | Lawrence Livermore National Laboratory |
| **LPSS** | Long Pulse Spallation Source |
| **LQD** | Low-Q Diffractometer |
| **LSDS** | Lead Slowing-Down Spectrometer |
| **LWTS** | Long-Wavelength Target Station |
| **m** | Meter |
| **mA** | milliAmpere |
| **µA** | microAmpere |
| **µc** | Micro Columbs |
| **µs** | microsecond |
| **meV** | milli-electron volt |
| **MeV** | Megaelectron volt |
| **MHz** | Megahertz |
| **ms** | millisecond |
| **MTS** | Materials Test Station |
| **MV** | Megavolts |
| **MW** | Megawatt |
| **NEP** | National Energy Policy of the Department of Energy |
| **NHMFL** | National High Magnetic Field Laboratory |
| **NIF** | National Ignition Facility |
| **NNSA** | National Nuclear Security Administration |
| **NPDF** | Neutron Powder Diffractometer |
| **NRS** | Neutron Resonance Spectroscopy |
| **ns** | nanosecond |
| **NSAC** | Nuclear Science Advisory Committee of the Department of Energy and National Science Foundation |
| **NSE** | Neutron Spin-echo |
| **NTS** | Nevada Test Site |
| **NUEX** | Neutron Experiment Detector |
| **NxGens** | Next Generation LPSS (Generation-III) |
| **ORNL** | Oak Ridge National Laboratory |
| **PCS** | Proton Crystallography Station |
| **PDF** | Pair-distribution-function |

| | |
|---|---|
| **PHAROS** | High-Resolution Chopper Spectrometer |
| **PHENIX** | Fast-spectrum Reactor, France |
| **Pu** | Plutonium |
| **pRad** | Proton Radiography |
| **ps** | picosecond |
| **PSR** | Proton Storage Ring |
| **P-T** | Pressure-Temperature |
| **QMU** | Quantification of Margins and Uncertainties |
| **QW** | Weak Charge |
| **R&D** | Research and Development |
| **Ra** | Radium |
| **RAM** | Random Access Memory |
| **RCS** | Rapid Cycling Synchrotron |
| **RF** | Radio Frequency |
| **RIA** | Rare Isotope Accelerator |
| **RFQ** | Radio Frequency Quadrupole |
| **RMM** | Repetition-rate Multiplication |
| **RSIS** | Radioactive Species Isotope Separator |
| **RT** | Room Temperature |
| **SANS** | Small-angle Neutron Scattering |
| **SC** | Superconducting |
| **SCD** | Single-crystal Diffractometer |
| **SCL** | Side-coupled LINAC |
| **SM** | Standard Model |
| **SMARTS** | Spectrometer for Materials Research at Temperature and Stress |
| **SNL** | Sandia National Laboratories |
| **SNM** | Special Nuclear Material |
| **SNS** | Spallation Neutron Source at Oak Ridge National Laboratory |
| **SPEAR** | Surface Profile Analysis Reflectometer |
| **SPR** | Sandia Pulsed Reactor at Sandia National Laboratories |
| **SPSS** | Short Pulse Spallation Source |
| **SNM** | Special Nuclear Material |
| **SRD** | Secret Restricted Data |
| **SSP** | National Nuclear Security Administration’s Stockpile Stewardship Program |
| **STS** | Stockpile to Target Sequence |
| **TRIUMP** | Tri-University Meson Facility, Canada |
| **THREX** | Threshold Experiment |
| **TMRS** | Target Moderator Reflector System |
| **TOF** | Time-of-flight |
| **TPC** | Total Project Cost |
| **UCN** | Ultracold Neutron |
| **UCNA** | Ultracold Neutron Alliance |
| **UGT** | Underground Test |
| **USANS** | Ultra-small Angle Neutron Scattering |
| **WNR** | Weapons Neutron Research Facility |